



INVASIVE PLANTS AND POLLINATION OF ALASKAN BERRY SPECIES:
INTEGRATING ECOLOGY AND EDUCATION

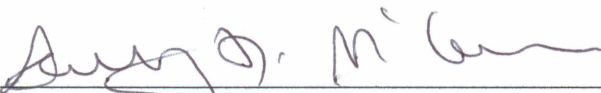
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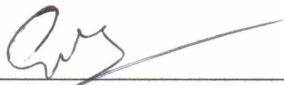
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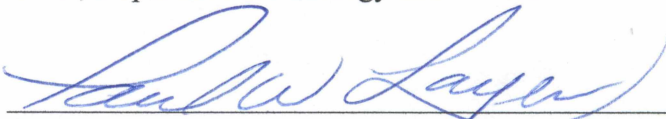

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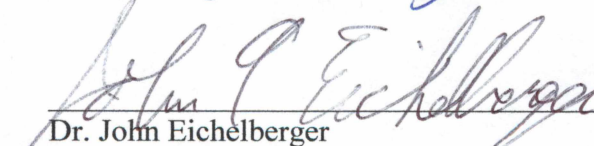

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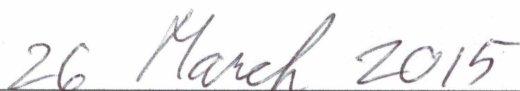

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INVASIVE PLANTS AND POLLINATION OF ALASKAN BERRY SPECIES:
INTEGRATING ECOLOGY AND EDUCATION

A
DISSERTATION

Presented to the Faculty
of the University of Alaska Fairbanks

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for the Degree of

DOCTOR OF PHILOSOPHY

By
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ABSTRACT

A rapidly changing climate and human disturbance patterns have accelerated the spread of invasive plants species in Alaska. Non-native plant invasions can disrupt pollinator services to native plants and have the potential to impact the pollination and fruit set in berry species important for subsistence harvest. My dissertation aims to address the dual need for greater understanding of the impacts of invasive plants on pollination of berry species in boreal ecosystems and the need for research on education strategies that best prepare Alaskans to respond to the issue. I integrate an ecological field experiment, a citizen science program where data is used to validate phenology models derived from herbarium data, and an invasive plants education experiment testing the effects of a metacognitive learning intervention to provide multiple perspectives that inform the management of invasive plants in Alaska. The ecological field experiment found that invasive *Melilotus albus* acts as a magnet species for pollinators, which increased seed production in *Vaccinium vitis-idaea*, slightly decreased pollination in *Rhododendron groenlandicum*, and had no detectable interactions with *Vaccinium uliginosum*. The impact *M. albus* had on *R. groenlandicum* changed with distance from the invasive plant patch, but the impact on *V. vitis-idaea* did not. Using data from a statewide citizen science program monitoring the phenology of these species, I found that herbarium-based phenology models were valid for assessing relative shifts in phenology of these species across Alaska. Employing the research on *M. albus* and the berry species as a test case, I found that students who received the metacognitive learning intervention show long-term improvement in metacognitive skills compared to students in the control group, but that the groups did not differ in their ability to apply resilience thinking skills to the environmental problem-solving. I synthesized social-ecological resilience and education research to investigate how citizen science

and metacognitive learning could contribute to the capacity of Alaskans to respond to social-ecological change. Together, the ecology and education research presented here provide diverse perspectives on how to best manage and build the human capacity to manage *M. albus* near subsistence plant species.

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CHAPTER 1

Introduction

**Non-native plant invasions and pollination of Alaskan berry species: integrating ecology
and education using a social-ecological systems research framework**

Invasive plants in a changing Alaska

Invasive species are among the top causes of changes in ecosystem services and losses in biodiversity around the globe (Wilcove et al. 1998, Sala et al. 2000, MEA 2005). Non-native plant invasions can change ecosystem properties such as nutrient cycling (Vitousek and Walker 1989; Evans et al. 2001; Mack et al. 2001), hydrology (Busch and Smith 1995; Rickard and Vaughan 1988), fire regimes (Whisenant 1990; D'Antonio and Vitousek 1992; Grigulis et al. 2005) and plant–pollinator interactions (review in Morales and Traveset 2008). The ecological consequences of non-native plant invasions also can affect the ecosystem services that sustain human well-being (e.g. water-filtration, food production, etc.; Pejchar and Mooney 2009).

People who rely most on the land for provisions such as food, medicine, and fuel are the most at risk of being affected by the changes in ecosystem services caused by invasive species (Díaz et al. 2006). In Alaska, a high proportion of the population participate in subsistence lifestyles, a specific way of living and relating to the land in which wild animals and plants are harvested for food or cultural practices (Loring and Gerlach 2009). Invasive plant species could decrease the abundances of important subsistence plant species by competing with them for light, water, space, or pollinators (cf. Skurski et al. 2014). There is also potential for large scale plant invasions to change the habitat or behaviors of subsistence wildlife species like salmon or moose (cf. Spellman and Martin 2010; Seefeldt et al. 2010; Lisuzzo et al. 2011; Roon et al. 2014). As a result, invasive plant species present a potential threat to the food security of many Alaskans, particularly those who cannot substitute purchased goods for subsistence food.

A rapidly changing climate in Alaska has made its ecosystems and the people who depend on them increasingly vulnerable to this threat (Jarnevich et al. 2014, Carlson et al. 2014). In the past, a cold climate and limited human population were thought to restrict the movement

of non-native plants into northern ecosystems (Callaghan et al. 1995). Climate largely controls the distribution of plants globally (Salisbury 1926; Woodward 1987), and the short growing season, cold winters, and large areas underlain by permafrost preclude many temperate species from establishing at high latitudes. Warmer winters (Chapman and Walsh 1993) and longer growing seasons (Myneni et al. 1997) have made conditions suitable for species that were previously limited to ecosystems further south. Simultaneously, anthropogenic disturbances have increased in Alaska due to increases in human population, commerce, and road construction (Walker and Walker 1991; Carlson and Shephard 2007; U.S. Census 2010). In Alaska today, both the diversity and extent of non-native plant species has dramatically increased (Carlson and Shephard 2007; Conn et al. 2010b; AKEPIC 2015a) with approximately 13 new species and 7,000 new populations being added to state records every year (Flagstad et al. 2011).

While invasive plants have largely remained restricted to areas of human disturbance in Alaska, invasives have begun to move into natural disturbance areas (e.g. wildfire burn scars, glacial floodplains) and intact boreal plant communities (Wurtz et al. 2006; Cortés-Burns et al. 2007; Lapina et al. 2007, Conn et al. 2008a; Villano and Mulder 2008; Bella 2011; Spellman and Wurtz 2011; Spellman et al. 2014, AKEPIC 2015a). Warmer temperatures and changes in precipitation have increased fire frequency, extent and severity in Alaska (Overpeck et al. 1997; Stocks et al. 2000; Bachelet et al. 2005; Balshi et al. 2009). Flooding regimes have also shifted in riparian systems of interior Alaska (Jones 2014). The changes in these two major disturbance regimes pose unpredictable circumstances for the spread of invasive plants in intact boreal plant communities.

Increasing opportunities for introduction and spread have also been documented in Alaska. For example, imported straw, hay, and horticultural commodities have brought invasive

plant propagules to Alaska of species without previously established populations (Conn et al. 2008b, 2010a). The diversity of agricultural weed species in Alaska has also increased over the past two decades (Conn et al. 2010b). Moose herbivory and snow machines catching seed-bearing stems from above the snow surface have been documented as mechanisms for spread of invasive *Melilotus albus* Medik. (Seefeldt et al. 2010, 2011). Recreational activities such as hiking and backpacking have also facilitated the spread of non-native plants in Alaska (Bella 2011). Many other probable mechanisms for invasive plant introduction and spread in Alaska remain unstudied.

Boreal ecosystems comprise one third of the world's forested land (Shugart et al. 1992) and cover the second largest area of any terrestrial biome (Pielou 1988). Despite their size and global distribution, little is known about the consequences of non-native plant invasions in boreal systems. In Alaska, only a few studies in the peer-reviewed literature have investigated the effects of invasive plants on boreal ecosystems. One study found that *Melilotus albus* growing in dense patches on glacial river floodplains competes with native species for light and can reduce seedling recruitment in some species (Spellman and Wurtz 2011). Another study investigated the per-gram competitive impacts of *M. albus* from different populations around the state of Alaska (Sowerwine et al. 2012). *M. albus* had a consistently competitive effect when grown at different densities with a native grass, but the effect did not vary with the source population. A third study used a leaf pack experiment to investigate the impact of the non-native shrub *Prunus padus* L. on food webs in salmon streams where it has invaded in Anchorage, Alaska (Roon et al. 2014). The *P. padus* leaves broke down more slowly than the leaves of the native riparian trees and shrubs that it displaces, but they did not support different stream macroinvertebrate communities. There

is a great need for more research on the impacts of invasive plants in Alaska, particularly with regard to their threats to subsistence food resources.

Invasive plants and the pollination of subsistence species

Sweetclover (*Melilotus albus*) is one of the most widespread invasive plants in Alaska (AKEPIC 2015a). This non-native has an extremely high number of flowers (up to 350,000 flowers per plant; Royer and Dickinson 1999) and offers considerable nectar and pollen resources to pollinators (Peterson 1989; Malacalza et al. 2005; Tepedino et al. 2008). Sweetclover can grow adjacent to co-flowering subsistence plant species such as blueberry (*Vaccinium uliginosum* L.), lowbush cranberry (or lingonberry, *Vaccinium vitis-idaea* L.), and Labrador tea (*Rhododendron groenlandicum* Oeder (formerly *Ledum groenlandicum*; Villano and Mulder 2008). *Vaccinium uliginosum* and *Vaccinium vitis-idaea* are an important part of subsistence diets across Alaska and are of increasing commercial importance (Ballew et al. 2004; Quiner 2005; Holloway 2006; Nelson et al. 2008). *Rhododendron groenlandicum* is used as a tea and to treat ailments such as colds and sore throats (Lepofsky et al. 1985; Pojar and MacKinnon 1994). All three of these species increase fruit and seed production when they are pollinated by insects (Hall and Beil 1970; Fröborg 1996; Jacquemart and Thompson 1996; Davis 2002; Wheelwright et al. 2006) and share pollinators with sweetclover (Turkington et al. 1978; Eckardt 1987; Davis et al. 2003; Dlusski et al. 2005; Tepedino et al. 2008). With overlapping habitat, flowering times, and pollinators, there is a high potential for sweetclover to alter pollination and reproduction of *V. uliginosum*, *V. vitis-idaea*, and *R. groenlandicum*.

Multiple plant-pollinator interaction scenarios are possible when an insect-pollinated invasive plant is introduced to a native plant community. In most published cases, invasive plants reduce pollinator visitation rates to native plants (Grabas and Lavery 1999, Chittka and

Schürkens 2001, Brown et al. 2002, Moragues and Traveset 2005, Totland et al. 2006; Traveset and Richardson 2006). They compete for pollinators through their high abundances and competitive reproductive traits such as the showy floral displays or numerous flowers (e.g. *Impatiens glandulifera*, Chittka and Schürkens 2001). If pollinators prefer the invasive flowers, non-native plant invasions can reduce pollen quantity delivered to the native plants (Waser 1983; Campbell 1985; Brown et al. 2002; Kandori et al. 2009). Non-native species can decrease pollen quality if they increase the amount of heterospecific pollen being delivered to the native plants (Morales and Traveset 2008). Some studies also observed decreases in fruit or seed production as a result of reduced pollen quality or quantity (Bjerknes et al. 2007, Muñoz and Cavieres 2008, Kandori et al. 2009).

Conversely, invasive plants could enhance reproductive success of native plants by acting as a “pollinator magnet” to increase the overall pollinator abundances for the entire plant community (Moragues and Traveset 2005, Tepedino et al. 2008). Further, in some cases, “sequential mutualisms” may be created by the presence of an invasive plant that provides floral resources during periods when the local native species are no longer flowering (cf. Waser and Real 1979). This scenario could increase the overall carrying capacity of a site for pollinator populations. Finally, there are a few cases published where no significant effects on plant-pollinator relationships were observed (Moragues and Traveset 2005).

Relative to other forest types, boreal forest ecosystems tend to have fewer flowering species, smaller pollinator pools, and shorter flowering periods (Kevan et al. 1993). This could intensify the potential impacts of non-native plant invasions on the reproductive success of nearby native plant species (cf. Carlson et al. 2008). I could find only a single study to date on the impact of invasive plants on the pollination and reproductive success of native plants in the

boreal forest that has been published in English in the peer reviewed literature (see Totland et al. 2006). This study investigated the effects of experimental outplanting of non-native *Phacelia tanacetifolia* on pollination and reproduction of a native boreal plant species (*Melampyrum pratense*; Totland et al. 2006). The non-native plants strongly decreased pollinator visitation to the native plants but did not change fruit set or seed production. Low nutrient availability in boreal forest habitats may explain why the substantial change in pollinator visitation to the native plant did not lead to a change in reproductive success. Further study is needed to disentangle the relative influence of pollen limitation and resource limitation on the impacts an invasive plant can have on native plant reproduction.

Role of education and outreach in managing invasive plants in Alaska

The potential for invasive plants to impact food resources such as the pollination of berry species presents an attractive opportunity for education and outreach. Alaska is still in the early stages of the invasion process for most non-native species that are present, and the majority of the species that have caused the greatest problems in other parts of the world have not yet been introduced to the state (AKEPIC 2015a). As a result, the general public is only just starting to become aware of invasive plant species, and education and outreach are a key component of Alaska's strategy for preventing new invasive plant introductions (Graziano 2011). Between 2007 and 2011, more than \$5.8 million was spent annually in Alaska to manage invasive species (Schwörer et al. 2012). Of that annual amount, most went directly to monitoring or controlling invasive species, but a substantial amount went to education and outreach (\$500,000; Schwörer et al. 2012).

Examples of the many successful invasive plant education and outreach programs include Alaska-specific K-12 curricula and teacher workshops (Slemmons 2007, Villano and Villano

2008), plant identification workshops (Flagstad et al. 2014), and a growing network of “Weed Smackdown” community awareness events (Etcheverry et al. 2011). These efforts aim to increase awareness and knowledge of the invasive plants issue in Alaska. However, given the accelerating rate of introductions and spread in Alaska (Carlson and Shephard 2007), other strategies may do more to aid the efforts to manage invasive plants. Effective and efficient invasive plants education should increase public awareness and ecological knowledge, but also increase problem-solving skills and civic engagement. Many Alaskan’s care greatly about wild berries, both as a food resource and as a cultural tradition (Ballew et al. 2004; Nelson et al. 2008). The topic of invasive plants affecting the pollination of berry species presents an emotional hook and context for engaging people in learning that could improve the management of invasives in Alaska.

Social-ecological systems perspective for non-native plants invasions in Alaska

Navigating complex social-ecological problems like non-native plant invasions requires the integration of research from multiple disciplines. The social-ecological systems concept asserts that human and ecological dimensions of a system are not only linked, but co-evolving and shaping one another (Chapin et al. 2009). Over the past few decades, ecologists have increasingly turned to the social-ecological systems perspective to understand the broader impacts their research has on society, including the production of science that helps sustain ecosystem services in the face of rapid global changes (Collins et al. 2011; Chapin et al. 2011). Interdisciplinary research on the resilience of social-ecological systems has been a key component of this effort (Gunderson and Holling 2002; Walker and Salt 2006; Chapin et al. 2009; Collins et al. 2011). Social-ecological resilience is defined as the capacity of the system to

respond to and shape change in ways that sustain and develop the fundamental function, structure, identity and feedbacks of the system (Chapin et al. 2009).

Learning is fundamental to social-ecological resilience (Folke et al. 2009). Learning processes allow humans in the system to reflect on how their actions have effected changes to the system and change their actions to allow for the system to return to a desired state if the change had undesired consequences (Argyris and Schön 1978; Senge 1990; Chapin et al. 2009; Kofinas 2009; Tidball and Krasny 2011). There is increasing evidence that well-designed education strategies or programs can target learning that increases this adaptive capacity (Fazey et al. 2007; Lundholm and Plummer 2010; Krasny et al. 2010; Muttarak and Lutz 2014), a key mechanism of resilience in social-ecological systems (Folke et al. 2002, Adger et al. 2005, Gallopín 2006, Janssen and Ostrom 2006, Engle 2011).

Given the importance of learning to resilience in social-ecological systems, integrating research from the fields of education and ecology may provide substantial benefits to any effort to respond to non-native plant invasions in Alaska. In Alaska, invasive plants research has focused primarily on risk analysis, assessment of ecosystem impacts, and inventory or monitoring of distributions (AKEPIC 2015b). Prior to this dissertation, no study had been published in Alaska on invasive plant education and outreach, despite the fact that effective education is one of the eight major priorities in the current Alaska strategic plan for the management of invasive plant species (Graziano 2011). A research framework that fully integrates both ecological and social aspects of non-native plant invasions, including the way Alaskans learn about them, would undoubtedly support the larger goals the state has to sustain “uninterrupted productivity of natural and agricultural resources” (Graziano 2011) in the face of accelerating non-native plant invasions. Further, this mission aligns well with the concept of

social-ecological resilience, and incorporating this concept into an invasive plants research framework may be well suited to support Alaska's strategic goal.

The National Science Foundation's Long-Term Ecological Research Program has proposed a social-ecological systems research framework to integrate social and natural science research (Collins et al. 2011). In this conceptual framework, the biophysical template represents the traditional realm of ecological research, while the social template represents the human dimensions of environmental change typically studied by social scientists (Fig. 1.1). The biophysical and the social dimensions of the system are linked through human actions and ecosystem services. Human behaviors can change the environment, which affects ecosystem structure and functioning. These changes can alter the services that the ecosystem provides to humans. Altered ecosystem services then shift the way people interact with and respond to the environment ("human outcomes" in Fig. 1.1), and may change the environmental behaviors or actions of humans. Human outcomes include characteristics that enable people to navigate social-ecological change such as human capital (skills and capabilities that enable a person to act in new ways; Coleman 1988), social capital (relationships between people that facilitate action; Coleman 1988), sense of place (a special feeling that develops in relationship to a particular social-ecological setting; Steele 1981), and stewardship values (ethics that embody the responsible care and management of social-ecological resources; Chapin et al. 2009).

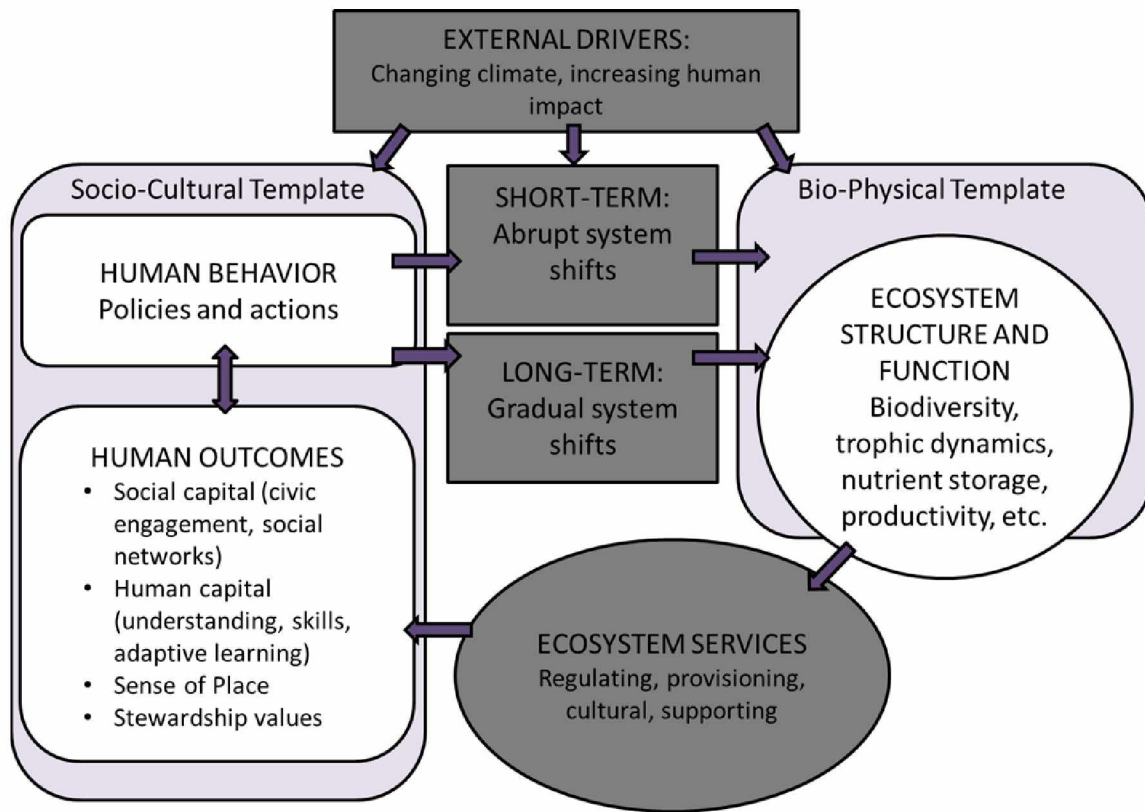


Figure 1.1 Integrated social-ecological system research framework adapted from Collins et al. (2011) and Tidball and Krasny (2010).

The framework allows for the investigation of these linkages in response to some external driver or multiple drivers of change, such as a warming climate or increasing human impact on the environment. The response of the system to these external drivers of change is represented by short-term pulses that alter the system (e.g., a flood or a stream restoration project) or more gradual changes to the system (e.g., sea level rise or a shift in stewardship values; Smith et al. 2009). Tidball and Krasny (2010) used and adapted this framework to investigate the impact environmental education programs have on resilience and sustainability in social-ecological systems. They propose that environmental education can produce both short-term boosts to maintaining valued ecosystem properties through service learning or community restoration projects, and long-term shifts in the skills and thinking capacities needed to manage and sustain resources over time.

Dissertation goals and approach

My dissertation aims to address the dual need for greater understanding of the impacts of invasive plants in boreal ecosystems and the need for research on education strategies that best prepare Alaskans to respond to the issue. The ecological research goal of this dissertation is to investigate the impact of an invasive plant species on the pollination and reproduction of native plants. The education research goal of this dissertation is to investigate the role two different education strategies, citizen science and metacognitive learning, can play in building resilience to non-native plant invasions in Alaska. I adapt the above integrated social-ecological systems research framework to situate these two efforts within a larger goal of sustaining subsistence berry resources in the face of accelerating non-native plant invasions in Alaska (Fig. 1.2).

To achieve the ecological research goal, I conducted a field experiment where I added small patches of *M. albus* to sites where *V. uliginosum*, *V. vitis-idaea*, and *R. groenlandicum* were growing abundantly. To address the education research goal of my dissertation, I engaged in two separate activities: 1) I initiated a citizen science program across Alaska that investigated the flowering overlap of *M. albus*, *V. vitis-idaea*, and *V. uliginosum*; and 2) I conducted an experiment on the impact of a metacognitive learning intervention on student ability to apply resilience thinking skills to the problem-solving scenario of *M. albus* and the pollination of berry species.

Ecological experiment

The ecological field experiment in chapter 2 investigated three questions: 1) Does *M. albus* addition alter pollination and reproduction of these native species? 2) Does the abundance of *M. albus* vary the effect it has on pollination and reproduction of the native plants? and 3) How important is the influence of *M. albus* relative to other factors expected to influence native

plant reproduction? In the first year of the experiment, I investigated all three species. Due to the limited overlap in flowering times of *V. uliginosum* with *M. albus* and logistical difficulties involved in outplanting *M. albus* prior to *V. uliginosum* flowering, the second year of study included only *V. vitis-idaea* and *R. groenlandicum*. Chapter 2 addresses the site-level effects of *M. albus* addition on pollination, fruit production, and seed set in *V. vitis-idaea* and *R. groenlandicum*. I report site-level results for *V. uliginosum* during the first year of study in Appendix 2.1.

Competition for resources such as light, water, or nutrients, however, operates directly on a plant neighborhood scale, while competition for pollinators occurs indirectly and can occur over both plant neighborhood scales and over the large foraging distances of pollinators (over 300 m in some *Bombus* spp.; Osborne et al. 1999). Chapter 3 addresses whether the effect of sweetclover varies with distance from the invasive plant patch within our sites. In that manuscript I address two questions: 1) Does the distance from the invasive plant patch affect pollination and seed production of *V. vitis-idaea* and *R. groenlandicum*? and 2) Does the relationship between distance from the invasive plant patch and native plant pollination and reproductive success vary with *M. albus* patch size?

Citizen science

Citizen science refers to partnerships between scientists and non-scientists to conduct scientific research on a topic of interest or concern (Conrad and Hilchey 2011, Jordan et al. 2012). Through the Melibee Project (“Meli-” which we use to represent *Melilotus albus*, the focal invasive plant species, and “-bee” for the primary pollinators it shares with the berry species), I worked with volunteer citizen scientists to monitor the phenology of our focal species across Alaska. The citizen science data complemented a historical phenology dataset that spanned

North America collected from herbarium specimens of the focal species. The Melibee Project had dual ecological research and education/outreach goals. The ecological research goals were: 1) provide a current snapshot of the flowering overlap of our three focal species across the state of Alaska, and 2) create an independent source of phenology data that could be used to validate the herbarium-based phenology models. The education and outreach goals for the network were to 1) engage public participants in meaningful research on the impacts of invasive plants on an important subsistence food resource in Alaska, and 2) increase knowledge and awareness of invasive plants, climate change, reproductive ecology of plants, and scientific practices among the participants.

The research goals for the citizen science network were motivated by the potential for the flowering overlap of sweetclover and the native focal species to vary across the different climates across Alaska. If the amount of overlap varied, the result would create a geographic mosaic of differing interactions between the species for pollinator services across the state. To address this question, we used phenology data gathered from herbarium records to model flowering times of sweetclover and the *Vaccinium* species. We then validated the models using the phenology observations made by citizen scientists. Chapter 4 presents the methodologies and model validation results from this effort. A forthcoming manuscript will use the phenology models to predict which areas of Alaska have greatest overlap in flowering times between sweetclover and the berry species. In combination with risk models for the spread of sweetclover, my collaborators and I will identify regions of Alaska at highest risk of altered pollinator services. This effort aims to help resource managers in subsistence-based communities in Alaska to plan for active prevention or management of invasive plants in particularly vulnerable areas.

To achieve the education and outreach goals of the Melibee Project citizen science network, I recruited and trained volunteers from diverse communities and backgrounds throughout Alaska. All volunteers were trained through either a live online training or an in-person workshop prior to commencing data collection. Training opportunities ranged in length from one hour to intensive 3-day workshops. Volunteers primarily consisted of families, K-12 educators and youth, environmental education camp participants, Alaska Native tribal and traditional council environmental programs, nature centers, land management agencies, and interested individuals. Approximately 250 volunteers actively participated in the research and submitted data.

Citizen science has become an increasingly popular way to engage the public in science learning (Silvertown 2009; Bonney et al. 2014). Citizen science also provides benefits to participants such as increased ecological knowledge, science process skills, trust between community members and scientists, and a sense of place (Turnbull et al. 2000; Bäckstrand 2003; Brossard et al 2005; Jordan et al. 2011; Dickinson et al. 2012; Jordan et al. 2012; Pandya 2012). In Chapter 6, I reviewed the education and social-ecological resilience literature to investigate the linkages between citizen science and the capacity for communities to be resilient to undesirable changes. In Appendix A, I present results of Melibee Project participant surveys that gauge changes in knowledge, skills, and behaviors related to key attributes of resilient social-ecological systems.

Metacognition

Metacognition, or the knowledge of and ability to regulate one's own thinking, has been suggested as an important approach to learning that could help increase the thinking skills in people necessary for social-ecological resilience (Fazey et al. 2005, Fazey et al. 2007).

Metacognitive learning strategies could improve skills like ecological literacy, innovative application of scientific knowledge, critical thinking, systems thinking, scenarios thinking, and bold decision making in the face of uncertainty. I review the relationships between metacognition and these thinking skills in the introduction to Chapter 5 and in Chapter 6, and experimentally test the impact of a metacognitive learning intervention on student ability to apply these skills to social-ecological problem solving in Chapter 5.

To support teacher and school participation in the Melibee Project citizen science program, I developed a set of inquiry-based activities for classroom use (Spellman 2011). I used the ecological research presented in chapters 2 and 3 of this dissertation as a context for learning about the complex social and ecological dimensions of non-native plant invasions and their effects on natural resources. These lessons were field tested in partnership with a 7th grade biology teacher in interior Alaska near Fairbanks. During the implementation of these inquiry lessons, I conducted the experiment presented in Chapter 5, in which I tested the effects of a metacognitive learning intervention on student ability to apply resilience thinking skills to invasive plants problem-solving. Before and after the experiment, students were asked to complete a written assessment designed to use the ecological research on sweetclover and the pollination of subsistence berry plants as a problem-solving scenario to which students could apply the suite of target resilience thinking skills. This work gives insight into whether training in metacognition could enhance the effective problem-solving of community.

Synthesizing ecology and education research

Each chapter in my dissertation presents a different insight or perspective that can help to manage subsistence plant resources and invasive plants as human disturbance patterns and climate rapidly change in Alaska. In figure 1.2, I conceptualize my study system and the way

each major component of the dissertation (ecological experiment, citizen science, and metacognition) interacts within the system.

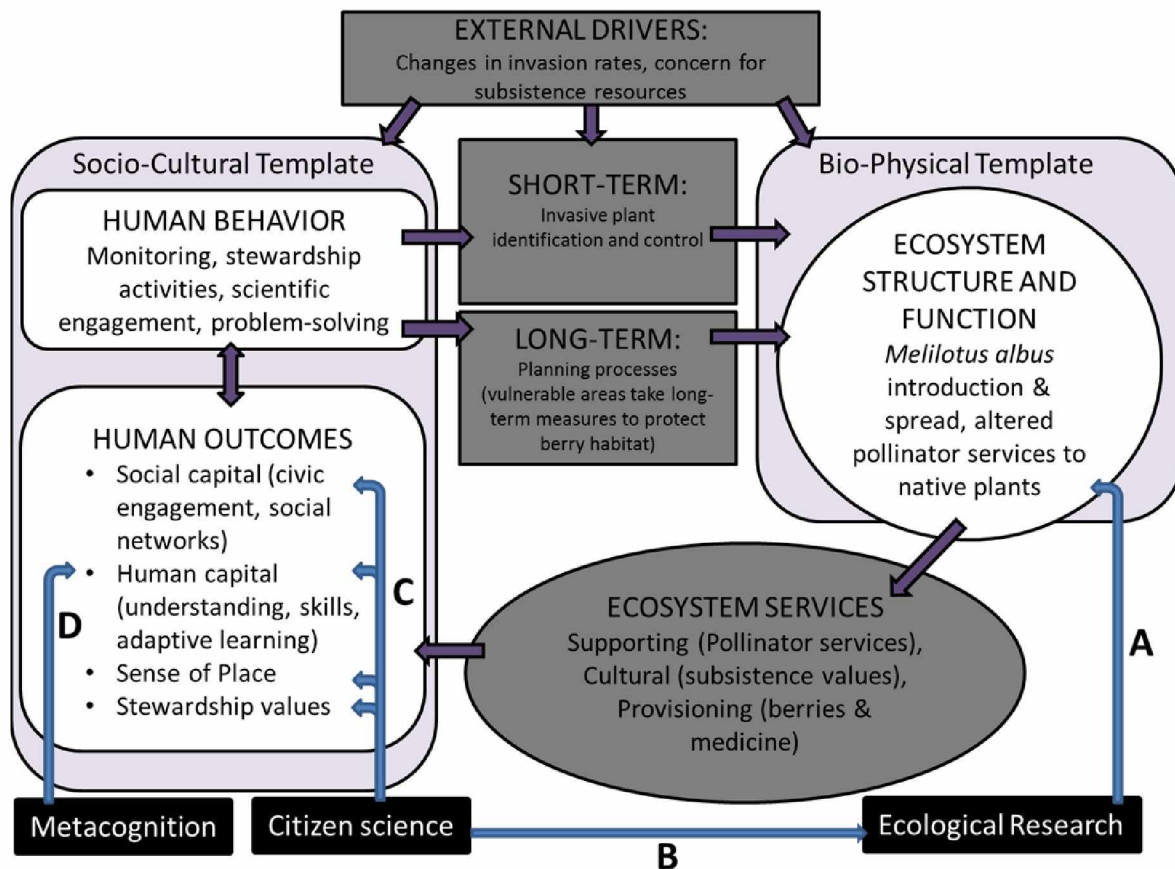


Figure 1.2 Conceptual framework defining the integrated dissertation study system. The contribution that each major dissertation component (ecological research, citizen science, and metacognition experiment) offers to the understanding of the system is indicated by linkages A-D. Framework adapted from Tidball and Krasny (2010) and Collins et al. (2011).

First, the ecological experiment (Chapters 2 & 3) establishes whether or not invasive *Melilotus albus* has an impact on the pollination of subsistence plants (Fig. 1.2 linkage A). It also provides insight into the role key variables that are useful for prioritizing management activities play in modifying the effects of sweetclover on native plants. Such variables include invasive plant patch size, identity of the native species, habitat type, and spatial relationships between species within a site. The citizen science program (Chapter 4) provides further perspective on

the functioning of the ecosystem by ultimately helping to identify areas where the interactions between *M. albus* and the berry species might be the strongest (Figure 1.2, linkage B). My hope is that by communicating these results to those with stewardship responsibilities (i.e. land managers, land owners, concerned community members), Alaskans will have increased capacity to respond with appropriate and scientifically informed actions and planning processes.

Knowing the impact non-native plants have on subsistence plant resources alone does not ensure that Alaskan communities will have the capacity to respond to the issue. In addition to financial capital, the community must also possess the problem-solving skills (i.e. human capital in fig. 1.2), social networks (i.e. social capital), sense of place, and stewardship values to sustainably manage their subsistence plant resources and shape the trajectory of change in the social-ecological system (Chapin et al. 2009). Chapters 5 and 6 and Appendix A provide insight into whether citizen science and metacognitive learning are viable educational strategies for increasing these sorts of attributes in a community. In the conclusion chapter, I will return to this conceptual model to summarize the major findings and potential applications my research provides for preparing Alaskans to respond to non-native plant invasions.

Literature cited

- Adger WN, Arnell NW, Tompkins EL (2005) Successful adaptation to climate change across scales. *Global Environmental Change* 15: 77–86
- AKEPIC -Alaska Exotic Plant Information Clearing House (2015a) AKEPIC Mapping Project Inventory Field Data. University of Alaska Anchorage Alaska Natural Heritage Program and USDA Forest Service, Anchorage, Alaska. Retrieved 27 January 2015 from <http://akweeds.uaa.alaska.edu/>
- AKEPIC -Alaska Exotic Plant Information Clearing House (2015b) AKEPIC Publications. University of Alaska Anchorage Alaska Natural Heritage Program and USDA Forest Service, Anchorage, Alaska. Retrieved 27 January 2015 from <http://aknhp.uaa.alaska.edu/botany/akepic/publications/>
- Argyris C, Schön D (1978) *Organizational learning: a theory of action perspective*. Addison-Wesley, Reading, MA, USA
- Bachelet D, Lenihan J, Neilson R, Drapek R, Kittel T (2005) Simulating the response of natural ecosystems and their fire regimes to climatic variability in Alaska. *Canadian Journal of Forest Research* 35: 2244-2257
- Bäckstrand K (2003) Civic science for sustainability: reframing the role of experts, policy-makers and citizens in environmental governance. *Global Environmental Politics* 3:24-41
- Ballew C, Ross A, Wells RS, Hiratsuka V, Hamrick KJ, Nobmann ED, Bartell S (2004) Final Report on the Alaska Traditional Diet Survey. Anchorage, AK: Alaska Native Health Board, Alaska Native Epidemiology Center.

- Balshi MS, McGuire AD, Duffy PA, Flannigan M, Walsh J, Melillo JM (2009) Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. *Global Change Biology* 15: 578–600
- Bella EM (2011) Invasion prediction on Alaska trails: distribution, habitat, and trail use. *Invasive plant Science and Management* 4:296-305
- Bjerknes AL, Totland T, Hegland SJ, Nielsen A (2007) Do alien plant invasions really affect pollination success in native plant species? *Biological Conservation* 138:1–12
- Bonney R, Shirk JL, Phillips TB, Wiggins A, Ballard HL, Miller-Rushing AJ, Parrish JK (2014) Next steps for citizen science. *Science* 343:1436-1437
- Brossard D, Lewenstein B, Bonney R (2005) Scientific knowledge and attitude change: The impact of a citizen science project. *International Journal of Science Education* 27:1099–1121.
- Brown BJ, Mitchell RJ, Graham SA (2002) Competition for pollination between an invasive species (purple loosestrife) and a native congener. *Ecology* 83:2328–2336
- Busch DE, Smith SD (1995) Mechanisms associated with decline of woody species in riparian ecosystems of the Southwestern US. *Ecological Monographs* 65:347-370
- Callaghan TV, Jonasson S, Nichols H, Heywood RB, Wookey PA (1995) Arctic terrestrial ecosystems and environmental change. *Philosophical Transactions: Physical Sciences and Engineering* 352: 259-276
- Campbell DR (1985) Pollinator sharing and seed set of *Stellaria pubera*: competition for pollination. *Ecology* 66:544–563

- Carlson ML, Shephard M (2007) Is the spread of non-native plants in Alaska accelerating? In: Harrington TB, Reichard SH (eds) Meeting the Challenge: Invasive Plants in Pacific Northwestern Ecosystems, PNW-GTR-694. Portland, Oregon: USDA, Forest Service, PNW Research Station.
- Carlson ML, Lapina IV, Shephard M, Conn JS, Densmore R, Spencer P, Heys J, Riley J, Nielsen J (2008) Invasiveness ranking system for non-native plants of Alaska. Technical Paper R10-TP-143, USDA Forest Service, Alaska Region, Anchorage, AK.
- Carlson ML, Trammell EJ, Aisu M, and Flagstad L (2014) Exploring vulnerabilities of arctic and subarctic Alaska to non-native plant invasion in BLM rapid ecoregional assessments. Proceedings from the 15th annual Alaska Invasive Species Conference. October 19-21, Anchorage, Alaska.
- Chapin FS III, Kofinas G, Folke C (2009) Principles of ecosystem stewardship: Resilience for based resource management in a changing world. Springer. New York, NY
- Chapin FS III, Power ME, Pickett STA, Freitag A, Reynolds JA, Jackson RB, Lodge DM, Duke C, Collins SL, Power AG, Bartuska A (2011) Earth stewardship: science for action to sustain the human-earth system. *Ecosphere* 2:89
- Chapman WL, Walsh JE (1993) Recent variations of sea ice and air temperature in high latitudes. *Bulletin of the American Meteorological Society* 74: 33-47
- Chittka L, Schürkens S (2001) Successful invasion of a floral market. *Nature* 411:653
- Coleman J (1988) Social capital in the creation of human capital. *American Journal of Sociology* 94:95–120

- Collins SL, Carpenter SR, Swinton SM, Orenstein DE, Childers DL et al. (2011) An integrated conceptual framework for long-term social–ecological research. *Frontiers in Ecology and the Environment* 9:351–357
- Conn JS, Beattie KL, Shephard ML, Carlson ML, Lapina I, Hebert M, Gronquist R, Densmore R, Rasy M (2008a) Alaska *Melilotus* invasions: distribution, origin, and susceptibility of plant communities. *Arctic, Alpine, and Antarctic Research* 40:298–308
- Conn JS, Stockdale CA, Morgan JC (2008b) Characterizing pathways of invasive plant spread to Alaska: propagules from container-grown ornamentals. *Invasive Plant Science and Management* 1:331-336
- Conn JS, Stockdale CA, Werdin-Pfisterer NR, Morgan JC (2010a) Characterizing pathways of invasive plant spread to Alaska: II. propagules from imported hay and straw. *Invasive Plant Science and Management* 3: 276-285
- Conn JS, Werdin-Pfisterer NR, and Beattie KL (2010b) Development of the Alaska agricultural weed flora 1981-2004: a case for prevention. *Weed Research* 51: 63-70.
- Conrad CC, Hilchey KG (2011) A review of citizen science and community-based environmental monitoring: issues and opportunities. *Environmental Monitoring and Assessment* 176:273–291.
- Cortés-Burns H, Lapina I, Klein S, Carlson ML (2007) BLM-BAER final report- invasive plant species monitoring and control: areas impacted by 2004 and 2005 fires in interior Alaska. Technical report on file with Alaska Natural Heritage Program Anchorage, Alaska
- D’Antonio CM, Vitousek PM (1992) Biological invasions by non-native grasses, the grass/fire cycle and global change. *Annual Review of Ecology and Systematics* 3: 67-87

- Davis AN (2002) Pollination biology of the lingonberry, *Vaccinium vitis-idaea* subsp. *minus* L. Master's Thesis. University of Alaska Fairbanks, Fairbanks, Alaska.
- Davis AN, Holloway PS, Kruse JJ (2003) Insect visitors and potential pollinators of lingonberries, *Vaccinium vitis-idaea* subsp. *minus*, in sub-arctic Alaska. *Acta Horticulturae* 626: 441-446
- Díaz S, Fargione J, Chapin FS III, Tilman D (2006) Biodiversity loss threatens human well-being. *PLoS Biology* 4(8): e277
- Dickinson JL, Shirk J, Bonter D, Bonney R, Crain RL, Martin J, Phillips T, Purcell K (2012) The current state of citizen science as a tool for ecological research and public engagement. *Frontiers in Ecology and the Environment* 10: 291–297
- Dlusski GM, Glazunova KP, Perfilieva KS (2005) Mechanisms that limit pollinator range in Ericaceae. *Zhurnal Obshchei Biologii* 66:224-238
- Eckardt N (1987) Element stewardship abstract for *Melilotus alba* – sweetclover or white sweetclover, *Melilotus officinalis* – yellow sweetclover. The Nature Conservancy, Minneapolis
- Engle NL (2011) Adaptive capacity and its assessment. *Global Environmental Change* 21: 647-656
- Etcheverry D, Stallard T, Chumley J (2011) Alaska weed smackdowns. Proceedings from the 12th annual Alaska Invasive Species Conference. October 19-21, Anchorage, Alaska
- Evans RD, Rimer R, Sperry L, Belnap J (2001) Non-native plant invasion alters nitrogen dynamics in an arid grassland. *Ecological Applications* 11: 1301-1310
- Fazey I, Fazey JA, Fazey DMA. 2005. Learning more effectively from experience. *Ecology and Society* 10: 4

- Fazey I, Fazey JA, Fischer J, Sherren K, Warren J, Noss RF, Dovers SR (2007) Adaptive capacity and learning to learn as leverage for social-ecological resilience. *Frontiers in Ecology and the Environment* 5: 375-380
- Flagstad L, Carlson ML, Cortés-Burns H, Jarnevich C, Holcombe T (2011) Will a changing climate increase interaction between rare and non-native plant species in Alaska? In Gible WJ, Combs JK, Reichard SH (eds) *Conserving Plant Biodiversity in a Changing World: A View from Northwestern North America*. Conference Proceedings. University of Washington Botanic Gardens, Seattle, Washington. 106 pp.
- Flagstad L, Cortés-Burns H, Greenstein C (2014) *Identification of Non-native Plants in Alaska*. Alaska Natural Heritage Program, University of Alaska Anchorage, AK. 251 pp.
- Folke C, Chapin FS III, Olsson P (2009) Transformations in ecosystem stewardship. In Chapin FS III, Kofinas GP, Folke C (eds) *Principles of ecosystem stewardship: Resilience-based natural resource management in a changing world*. Springer, New York, NY
- Folke C, Carpenter S, Elmqvist T, Gunderson L, Holling CS, Walker B (2002) Resilience and sustainable development: building adaptive capacity in a world of transformations. *AMBIO: A Journal of the Human Environment* 31:437-440
- Fröberg H (1996) Pollination and seed production in five boreal species of *Vaccinium* and *Andromeda* (Ericaceae). *Canadian Journal of Botany* 74:1363-1368
- Gallopín GC (2006) Linkages between vulnerability, resilience, and adaptive capacity. *Global Environmental Change* 16: 293–303
- Grabas GP, Lavery TM (1999) The effect of purple loosestrife (*Lythrum salicaria* L; Lythraceae) on the pollination and reproductive success of sympatric co-flowering wetland plants. *Ecoscience* 6: 230-242

- Graziano G (2011) Strategic plan for invasive weed & agricultural pest management and prevention in Alaska. Alaska Plant Materials Center, Division of Agriculture, Department of Natural Resources, Palmer, AK. 36 pp.
- Grigulis K, Lavorel S, Davies ID, Dossantos A, Lloret F, Vila M (2005) Landscape-scale positive feedbacks between fire and expansion of large tussock grass, *Ampelodesmos mauritanica* in Catalan shrublands. *Global Change Biology* 11:1042-1053
- Gunderson LH, Holling CS (2002) Panarchy: understanding transformations in human and natural systems. Island Press, Washington, D.C., USA
- Hall IV, Beil CE (1970) Seed germination, pollination, and growth of *Vaccinium vitis-idaea* var. *minus* Lodd. *Canadian Journal of Plant Science* 50:731-732
- Holloway PS (2006) Managing wild bog blueberry, lingonberry, cloudberry, and crowberry stands in Alaska. Report for University of Alaska Fairbanks and Natural Resource Conservation Service, Fairbanks, AK
- Jacquemart AL, Thompson JD (1996) Floral and pollination biology of three sympatric *Vaccinium* (Ericaceae) species in the upper Ardennes, Belgium. *Canadian Journal of Botany* 74:210-221
- Janssen MA, Ostrom E (2006) Resilience, vulnerability, and adaptation: A cross-cutting theme of the International Human Dimensions Programme on Global Environmental Change. *Global Environmental Change* 16:237-239
- Jarnevich CS, Holcombe TR, Bella EM, Carlson ML, Graziano G, Lamb M, Seefeldt SS, Morissette J (2014) Cross-scale assessment of potential habitat shifts in a rapidly changing climate. *Invasive Plant Management and Science* 7:491-502

- Jones CE (2014) Ecohydrological linkages: connecting the dots between hydrology, climate, and people of the North. Ph.D Dissertation. University of Alaska Fairbanks, Fairbanks, Alaska
- Jordan RC, Gray SA, Howe DV, Brooks WR, Ehrenfeld JG (2011) Knowledge gain and behavioral change in citizen-science programs. *Conservation Biology* 25:1148-1154
- Jordan RC, Ballard HL, Phillips TB (2012) Key issues and new approaches for evaluating citizen science learning outcomes. *Frontiers in Ecology and the Environment* 10: 307–309
- Kandori I, Hirao T, Matsunaga S, Kurosaki T (2009) An invasive dandelion unilaterally reduces the reproduction of a native congener through competition for pollination. *Oecologia* 159:559-569
- Kevan PG, Tikhmenev EA, Usui M (1993) Insects and plants in the pollination ecology of the boreal zone. *Ecological Restoration* 8:247–267
- Kofinas GP (2009) Adaptive co-management in social-ecological governance. In Chapin FS III, Kofinas GP, Folke C (eds) *Principles of ecosystem stewardship: Resilience-based natural resource management in a changing world*. Springer. New York, NY
- Krasny ME, Lundholm C, Plummer R (2010) Resilience in social–ecological systems: the roles of learning and education. *Environmental Education Research* 16:463–474
- Lapina IV, Klein SC, Carlson ML (2007) Non-native plant species of the Fairbanks region: 2005-2006 surveys. Technical report on file with Alaska Natural Heritage Program, Anchorage, Alaska.
- Lepofsky D, Turner NJ, Kuhnlein HV (1985) Determining the availability of traditional wild plant foods: an example of Nuxalk foods, Bella Coola, British Columbia. *Ecology of Food and Nutrition*. 16: 223-241.

- Lisuzzo N, Napoleon E, Smith G, Charles W, Mackey L, Paddock R III, Spellman KV, Spellman BT, Robinnette J, Cannon D, Hamilton J, et al. (2011) Kellutellra Alaska-m Ungalaqlirnera Eniaritulinun Itrallerkaaneng Kass' at Yup'it-Illu Qaneryaraitgun, Protecting Southwestern Alaska from invasive species: a guide in the English and Yup'ik Languages. US Forest Service—Alaska Region, Fairbanks, Alaska. 51 pp.
- Loring PA, Gerlach SC (2009) Food, culture, and human health in Alaska: an integrative health approach to food security. *Environmental Science and Policy* 12: 466–478
- Lundholm C, Plummer R (2010) Resilience and learning: A conspectus for environmental education. *Environmental Education Research* 16: 475–91
- Mack MC, D'Antonio CM, Ley R (2001) Alteration of ecosystem nitrogen dynamics by non-native plants: a case study of C4 grasses in Hawaii. *Ecological Applications* 11: 1323–1335
- Malacalza NH, Caccavari MA, Fagúndez G, Lupano CE (2005) Unifloral honeys of the province of Buenos Aires, Argentina. *Journal of the Science of Food and Agriculture* 85:1389–1396
- MEA- Millenium Ecosystem Assessment (2005) *Ecosystems and human well-being: synthesis*. Island Press. Washington D.C.
- Moragues E, Traveset A (2005) Effect of *Carpobrotus* spp. on the pollination success of native plant species of the Balearic Islands. *Biological Conservation* 122: 611–619
- Morales CL, Traveset A (2008) Interspecific pollen transfer: magnitude, prevalence and consequences for plant fitness. *Critical Reviews in Plant Sciences* 27:221–238

- Muñoz AA, Cavieres LA (2008) The presence of a showy invasive plant disrupts pollinator service and reproductive output in native alpine species only at high densities. *Journal of Ecology* 96:459–67
- Muttarak R, Lutz W (2014) Is education a key to reducing vulnerability to natural disasters and hence unavoidable climate change? *Ecology and Society* 19(1): 42
- Myneni RB, Keeling CD, Tucker CJ, Asrar G, Nemani RR (1997) Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* 386: 698-702
- Nelson JL, Zavaleta E, Chapin FS III (2008) Boreal fire effects on subsistence resources: landscape diversity as a critical component of rural livelihoods in Alaska and adjacent Canada. *Ecosystems* 11:156-171
- Osborne JL, Clark SJ, Morris RJ, Williams IH, Riley JR, Smith AD et al. (1999) A landscape-scale study of bumble bee foraging range and constancy, using harmonic radar. *Journal of Applied Ecology* 36: 519–533
- Overpeck JT, Hughen K, Hardy D, Bradley R, Case R, Douglas M, Finney B (1997) Arctic environmental change of the last four centuries. *Science* 278: 1251-1256
- Pandya RE (2012) A framework for engaging diverse communities in citizen science in the US. *Frontiers in Ecology and the Environment* 10: 314–317
- Pejchar L, Mooney HA (2009) Invasive species, ecosystem services and human well-being. *Trends in Ecology and Evolution* 24:497-504
- Peterson SF (1989) Beekeeping under the northern lights. *American Bee Journal* 129:33-35
- Pielou EC (1988) *The world of northern evergreens*. Cornell University Press, Ithaca, New York
- Pojar J, MacKinnon A (1994) *Plants of the Pacific Northwest Coast: Washington, Oregon, British Columbia and Alaska*. Redmond, WA: Lone Pine Publishing. 526 p.

- Quiner M (2005) Ranchers get the blues: area citizens consider branching out into berries.
Peninsula Clarion, October 11, 2005, <http://www.peninsulaclarion.com/stories/101105/>
- Rickard WH, Vaughan BE (1988) Plant community characteristics and responses. In Rickard WH, Rogers LE, Vaughan BE, Liebetrau SF (eds) Shrub-steppe: balance and change in a semi-arid terrestrial ecosystem. Elsevier, Amsterdam, Netherlands
- Roon DA, Wipfli MS, Wurtz TL (2014) Effects of invasive European bird cherry (*Prunus padus*) on leaf litter processing by aquatic invertebrate shredder communities in urban Alaskan streams. *Hydrobiologia* 736: 17-30
- Royer F, Dickinson R (1999) Weeds of the Northern U.S. and Canada. The University of Alberta press. 434 pp.
- Sala OE, Chapin FS III, Armesto JJ, Berlow E, Bloomfield J, Dirzo R, Huber-Sanwald E, Huenneke LF, Jackson RB, et al. (2000) Global biodiversity scenarios for the year 2100. *Science* 287: 1770-1774
- Salisbury EJ (1926) The geographical distribution of plants in relation to climatic factors. *Geographic Journal* 57: 312-335
- Schwörer T, Federer R, Ferren H (2012) Managing invasive species: how much do we spend? Technical report. Institute of Social and Economic Research, University of Alaska Anchorage
- Seefeldt SS, Collins WB, Kuhl JC, and Clauss M (2010) White sweetclover (*Melilotus albus*) and narrowleaf hawksbeard (*Crepis tectorum*) seed germination after passing through moose. *Invasive Plant Science and Management* 3:26-31

- Seefeldt SS, Craig T, Carr E, Kapla J (2011) Impact of snowmachine use on spread of white sweetclover seed. Proceedings from the 12th annual Alaska Invasive Species Conference. October 19-21, Anchorage, Alaska
- Senge PM (1990) The fifth discipline: the art and practice of the learning organization. Doubleday Currency Press, New York, New York
- Shugart HH, Leemans R, Bonan GB (1992) A systems analysis of the boreal forest. Cambridge University Press, Cambridge, UK
- Silvertown J (2009) A new dawn for citizen science. *Trends in Ecology and Evolution* 24: 467-471
- Skurski TC, Rew LJ, Maxwell BD (2014) Mechanisms underlying nonindigenous plant impacts: a review of recent experimental research. *Invasive Plant Science and Management* 7:432–444
- Slemmons C (2007) Invasive plants: taking root in Alaska. Homer Soil and Water Conservation District and Kenai Peninsula Cooperative Weed Management Area. Homer, Alaska
- Smith MD, Knapp AK, Collins SL (2009) A framework for assessing ecosystem dynamics in response to chronic resource alterations induced by global change. *Ecology* 90: 3279–89
- Sowerwine JE, Rinella MJ, Carlson ML (2012) Do populations of an invasive weed differ greatly in their per-gram competitive effects? *Western North American Naturalist* 72: 43-47
- Spellman BT, Martin M (2010) Managing reed canarygrass on the Kenai Peninsula: before, now, and the future. Conference Proceedings from the Kenai Peninsula Cooperative Weed Management Area Annual conference. Seward, AK

- Spellman BT, Wurtz T (2011) Invasive white sweetclover (*Melilotus alba*) impacts native recruitment along rivers in interior Alaska. *Biol Invas* 13:1779-1790
- Spellman KV (2011) Melibee Project classroom learning module: pollinator attraction K-12 lessons. <https://sites.google.com/a/alaska.edu/melibee-project/for-classrooms>
- Spellman KV, Mulder CPH, Hollingsworth TN (2014) Susceptibility of burned black spruce (*Picea mariana*) forests to non-native plant invasions in Interior Alaska. *Biological Invasions* 16:1879-1895
- Steele F (1981) The sense of place. CBI Publishing Company, Boston, Massachusetts, USA
- Stocks BJ, Fosberg MA, Wotton MB, Lynham TJ, Ryan KC (2000) Climate change and forest fire activity in North American boreal forests. In Kasischke ES, Stocks BJ (eds) Fire, climate change and carbon cycling in the boreal forest. Ecological Studies Series. Springer-Verlag, New York, New York, USA
- Tepedino VJ, Bradley BA, Griswold TL (2008) Might flowers of invasive plants increase native bee carrying capacity? Intimations from Capitol Reef National Park, Utah. *Natural Areas Journal* 28:44–50
- Tidball KG, Krasny ME (2010) Urban environmental education from a social-ecological perspective: conceptual framework for civic ecology education. *Cities and the Environment* 3(1):11
- Tidball KG, Krasny ME (2011) Toward an ecology of environmental education and learning. *Ecosphere* 2(2):21
- Totland Ø, Nielsen A, Bjerknes AL, Ohlson M (2006) Effects of an exotic plant and habitat disturbance on pollinator visitation and reproduction in a boreal forest herb. *American Journal of Botany* 93:868–873

- Traveset A, Richardson DM (2006) Biological invasions as disruptors of plant reproductive mutualisms. *Trends in Ecology and Evolution* 21:208-216
- Turkington RA, Cavers PB, Empel E (1978) The biology of Canadian weeds: 29. *Melilotus alba* Desr. and *M. officinalis* (L.) Lam. *Canadian Journal of Plant Science* 58:523-537
- Turnbull DJ, Bonney R, Bascom D, Cabral A. (2000) Thinking scientifically during participation in a citizen science project. *Science Education* 84:265–275
- U.S. Census (2010) Census 2010 Data for the State of Alaska. U.S. Census Bureau.
<http://www.census.gov/census2010/states/ak.html>
- Villano KL, Mulder CPH (2008) Invasive plant spread in burned lands of interior Alaska. Technical report for National Park Service-Alaska Region and National Aeronautics and Space Administration, Fairbanks, Alaska
- Villano KL, Villano CP (2008) Weed Wackers: K-6 educators guide to invasive plants of Alaska. Alaska Committee for Noxious and Invasive Plant Management. Fairbanks, AK. 256 pp
- Vitousek PM, Walker LP (1989) Biological invasions by *Myrica faya* in Hawaii: plant demography, nitrogen fixation and ecosystem effects. *Ecological Monographs* 59:247-265
- Walker BH, Salt D (2006) Resilience Thinking: sustaining ecosystems and people in a changing world. Island Press, Washington, D.C.
- Walker DA, Walker MD (1991) History and pattern of disturbance in Alaskan arctic terrestrial ecosystems: a hierarchical approach to analysing landscape change. *Journal of Applied Ecology* 28:244-276

- Waser NM (1983) Competition for pollination and floral character differences among sympatric plant species: a review of evidence. In Jones CE, Little RJ (eds) Handbook of experimental pollination biology. Van Nostrand Reinhold, New York, pp 277–293
- Waser NM, Real LA (1979) Effective mutualism between sequentially flowering plant species. *Nature* 281:670 – 672.
- Wheelwright NT, Dukeshire EE, Fontaine JB, Gutow SH, Moeller DA, Schuetz JG, Smith TM, Rodgers SL, Zink AG (2006) Pollinator limitation, autogamy and minimal inbreeding depression in insect-pollinated plants on a boreal island. *American Midland Naturalist* 155: 19-38
- Whisenant SG (1990) Changing fire frequencies on Idaho's Snake River plain: ecological and management implications. US Department of Agriculture, Forest Service Intermountain Research Station, General Report INT-276
- Wilcove DS, Rothstein D, Dubow J, Phillips A, Losos E (1998) Quantifying threats to imperiled species in the United States. *BioScience* 48: 607-615
- Woodward FI (1987) Climate and plant distribution. Cambridge University Press, Cambridge, UK
- Wurtz T, Macander M, Spellman BT (2006) Spread of an invasive plant on Alaska's roads and river networks. General Technical Report U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR

CHAPTER 2

Effects of non-native *Melilotus albus* on pollination and reproduction in two boreal shrubs¹

¹Spellman KV, Schneller LC, Mulder CPH, Carlson ML. Effects of non-native *Melilotus albus* on pollination and reproduction in two boreal shrubs. Manuscript submitted to the journal *Oecologia*, January 2015

Abstract

The establishment of abundantly flowered, highly rewarding non-native plant species is expected to have strong consequences for native plants through altered pollination services, particularly in boreal forest where the flowering season is short and the pollinator pool is small. We added flowering *Melilotus albus* to boreal forest sites in two different years to test if the invasive plant influences the pollination and reproductive success of two co-flowering ericaceous species: *Vaccinium vitis-idaea* and *Rhododendron groenlandicum*. We found that *M. albus* increased the pollinator diversity and tended to increase visitation rates to the focal native plant species compared to control sites. *M. albus* facilitated greater seed production per berry in *V. vitis-idaea* when we added 120 plants compared to when we added 40 plants or in control sites. Increasing numbers of *M. albus* inflorescences lowered conspecific pollen loads and percentage of flowers pollinated in *R. groenlandicum*; however no differences in fruit set were detected. The number of *M. albus* inflorescences had greater importance in explaining *R. groenlandicum* pollination compared to other environmental variables, and had greater importance in black spruce sites than in mixed deciduous and white spruce sites for explaining the percentage of *V. vitis-idaea* flowers pollinated. Our data suggest that the identity of new pollinators attracted to the invaded sites, degree of shared pollinators between invasive and native species, and variation in resource limitation among sites are likely determining factors in the reproductive responses of boreal native plants in the presence of an invasive.

Keywords

Fruit set, invasive species, *Ledum palustre* ssp. *groenlandicum*, seed set, *Rhododendron groenlandicum*, *Vaccinium vitis-idaea*

Introduction

Non-native plants that invade flowering plant communities can have diverse effects on reproductive success of native plants. Competitive effects of non-native plant introductions on native species occur through two often co-occurring mechanisms: 1) decreases in pollen quantity and 2) decreases in pollen quality (Waser 1978). Non-native plant invasions can reduce pollen quantity delivered to native plants by decreasing visitation rates to the native species as a result of pollinator preference for the invasive flowers (Waser 1983; Campbell 1985; Brown et al. 2002; Kandori et al. 2009). Non-native species can decrease pollen quality if they increase the amount of self- or heterospecific pollen being delivered (Morales and Traveset 2008). Conversely, some studies have demonstrated that the presence of invasive plants increased overall pollinator abundances or visitation rates to the entire community, which increased pollen quantity, fruit yield and seed production (Moragues and Traveset 2005; Tepedino et al. 2008). Other studies have found no measurable impacts of invasive plants on the pollination and reproduction of native plants (Bartomeus et al. 2008a).

The abundance of invasive plant flowers within the flowering plant community at a site changes pollen flow to the native plants and subsequent reproductive success (Muñoz and Cavieres 2008; Molina-Montenegro et al. 2008; Flanagan et al. 2010). The relative influence an invasive plant has on the reproduction of native plants may also vary with other factors that would be expected to affect plant reproduction, such as habitat type, weather, and inter- or intra-specific competition with other native flowers. Pollinator visitation rates can differ among different habitat types due to differences in conspecific and heterospecific flower abundances, amount of shade, or availability of pollinator nesting sites (Westrich 1996; Gathmann and Tschardt 2002; Westphal et al. 2003; Bartomeus et al. 2010). Differences in weather between

years or between sites can change pollination services by influencing the amount of time available for pollinator flight activity (Kuchko 1988, Tuell and Isaacs 2010), by affecting which types of pollinators are active (Corbet et al. 1993), and by directly affecting resources for flower and fruit growth and maintenance (Jacquemart 1997, Krebs et al. 2009).

Relative to other forest types, boreal forest ecosystems tend to have fewer flowering species, smaller pollinator pools, and shorter flowering periods (Kevan et al. 1993). This could intensify the potential negative or positive impacts of non-native plant invasions on the reproductive success of neighboring native plant species (cf. Carlson et al. 2008). Despite the fact that the boreal forest is one of the largest terrestrial biomes on Earth (a third of the world's forested land; Shugart et al. 1992), to date we could find only a single study on the impact of invasive plants on the pollination and reproductive success of native plants in the boreal forest that has been published in English in the peer reviewed literature (see Totland et al. 2006). This single study found that the experimental outplanting of non-native *Phacelia tanacetifolia* strongly decreased pollinator visitation to a native boreal plant species (*Melampyrum pratense*) but did not change fruit set or seed production (Totland et al. 2006). High resource limitations on plant reproduction in boreal forest habitats may explain why the substantial change in pollinator visitation to the native plant did not lead to a change in reproductive success. Without stigmatic pollen load data, however, the Totland et al. (2006) study could not disentangle the relative influence of pollen limitation and resource limitation on plant reproduction in their field sites.

Compared to other places, low levels of anthropogenic disturbance and cold climate have limited the introduction and survival rates of non-native plants in the boreal forest (Sanderson et al. 2012). However, the number of non-native species occurring within Alaska increased by 46%

between 1941 and 2006 (Carlson and Shephard 2007). Increases in the number and extent of non-native species in Alaska may be attributed in large part to increases in human population and associated disturbances (e.g. more roads, resource extraction; Walker and Walker 1991; U.S. Census Bureau 2010; Carlson and Shephard 2007) and increased influx of propagules via imported agricultural and horticultural commodities (Conn et al. 2008a). Climatic shifts in Alaska such as warmer winters (Serreze et al. 2000) and longer growing seasons (Myneni et al. 1997) have also increased the likelihood of invasive plant success.

A few species, such as *Melilotus albus* Medik. (*M. albus*), have spread rapidly throughout the state, primarily along road corridors (AKEPIC 2014). *M. albus* is one of the few non-native species in Alaska that has also spread widely into naturally disturbed areas such as river floodplains (Conn et al. 2008b; Spellman and Wurtz 2011) and wildfire scars (Spellman et al. 2014). *M. albus* is native to Eurasia and was introduced to Alaska in 1913 as a potential cold-hardy forage and nitrogen-fixing crop (Irwin 1945), and now occurs throughout Alaska from as far south as Metlakatla (55.122 °N, - 131.561 °W) to north of Coldfoot (67.286 °N, -150.171 °W) at the base of the Brooks Mountain Range (AKEPIC 2014). *M. albus* can reduce native seedling recruitment along glacial river floodplains by directly competing with native plants for light (Spellman and Wurtz 2011). Additionally, this species offers considerable nectar and pollen resources to floral visitors (Peterson 1989, Malacalza et al. 2005, Tepedino et al. 2008) with an extremely high number of flowers per plant (up to 350,000 flowers per plant; Royer and Dickinson 1999), particularly in comparison to native boreal insect-pollinated plants that offer less pollen and nectar rewards. As a result, *M. albus* invasions could also alter plant communities by changing the pollination and reproductive success of native boreal plants.

In many of the instances of *M. albus* invasion documented in or adjacent to burned boreal forest (Villano and Mulder 2008), the understory is dominated by *Vaccinium vitis-idaea* L. (lingonberry or lowbush cranberry) and *Rhododendron groenlandicum* (Oeder) Kron & Judd (formerly *Ledum palustre* ssp. *groenlandicum*; Labrador tea), two abundant insect-pollinated Ericaceous plant species that have broad circumboreal distributions (Hultén 1968). These species are of cultural, subsistence, and economic importance (Garibaldi 1999, Quiner 2005; Holloway 2006; Nelson et al. 2008). Because both species overlap with *M. albus* in habitat (Villano and Mulder 2008), flowering times (pers. obs.), and pollinator communities (Turkington et al. 1978; Eckardt 1987; Davis et al. 2003; Dlusski et al. 2005; Tepedino et al. 2008), we chose to focus on *V. vitis-idaea* and *R. groenlandicum* in this study.

Within interior Alaska, bumblebees (*Bombus* spp.), syrphid flies (Syrphidae), and solitary bees (*Andrena* sp.) are the pollinators that carry the greatest amount of *V. vitis-idaea* pollen (Davis et al. 2003), but other pollinator guilds carry its pollen as well (e.g. Lepidopterans, other flies, beetles; Davis 2002). *Rhododendron groenlandicum* is visited by pollinators in all the aforementioned guilds (pers. obs.). *M. albus* has generalist flowers visited by a wide range of species, including solitary bees, bumblebees, wasps, flies, butterflies, and moths (Coe and Martin 1920; Turkington et al. 1978; Tepedino et al. 2008). *V. vitis-idaea* and *R. groenlandicum* are self-compatible (Jacquemart and Thompson 1996; Jacquemart 1997; Wheelwright et al. 2006). Both species, however, have decreased fruit and seed set when insect pollinators are excluded and increase fruit set and seed production when they are supplemented with outcross pollen (Hall and Beil 1970; Fröborg 1996; Jacquemart and Thompson 1996; Davis 2002; Wheelwright et al. 2006). This was confirmed in interior Alaska, where flowers from which pollinators were excluded showed a 79% and 18% reduction in fruit set for *V. vitis-idaea* and *R. groenlandicum*,

respectively, compared to flowers open to insect pollination (Mulder and Spellman, unpublished data).

We conducted a preliminary observational study during the summer of 2010 to compare insect pollinator visitation to native plants and *V. vitis-idaea* fruit set at sites with and without *M. albus* along the roadside. These sites were located throughout interior Alaska, along the Steese, Elliot, and Dalton Highways. The abundance of insect pollinators observed at sites with flowering *M. albus* was approximately two times higher than at sites without *M. albus* (L. Schneller, unpublished data). The sites with *M. albus* also had greater proportion of *V. vitis-idaea* flowers setting fruit compared to sites without *M. albus* present ($49 \pm 20\%$ in sites with *M. albus*, $16 \pm 7\%$ in sites without *M. albus*; C.P.H. Mulder, unpublished data). However, we could not attribute these changes in pollinator activity and *V. vitis-idaea* fruit set to the presence of *M. albus*, as site conditions that favor *M. albus* establishment may also favor higher pollinator activity, and promote greater abundance of native flowers and greater fruit set. To disentangle potential confounding environmental effects, we conducted a controlled *M. albus* addition experiment, which we report here. Specifically, we ask three questions: 1) Does *M. albus* addition alter *V. vitis-idaea* and *R. groenlandicum* pollination and reproduction? 2) Does the abundance of *M. albus* vary the effect it has on pollination and reproduction of these native plants? and 3) How important is the influence of *M. albus* relative to other factors expected to influence native plant reproduction?

Methods

Study area

During the growing seasons in 2011 and 2012, we located boreal forest sites within the Bonanza Creek Boreal Long Term Ecological Research Program (BNZ LTER) research areas

near Fairbanks, Alaska (Bonanza Creek Experimental Forest, 64.709 °N, -148.326 °W, and Caribou and Poker Creeks Research Watershed, 65.141 °N, -147.457 °W. Sites were selected to contain flowering *V. vitis-idaea* and *R. groenlandicum*, and primarily occurred in two habitat types: 1) “mixed” sites that contain deciduous tree species (*Betula neoalaskana* Sarg. and/or *Populus tremuloides* Michx.) and white spruce (*Picea glauca* (Moench) Voss), and 2) black spruce (*Picea mariana* Mill.) sites (Fig. 2.1). The mixed sites tended to occur on gentle hill slopes (3-10% grade) or at the tops of hills with understory vegetation composed primarily of the two focal species, *Vaccinium uliginosum*, *Rosa acicularis*, *Viburnum edule*, *Salix* spp., *Alnus viridis*, *Geocaulon lividum*, and *Cornus canadensis*. The black spruce sites occurred in low lying areas with minimal slope (0-3% grade) and understory vegetation composed primarily of the two focal species, *Vaccinium uliginosum*, *Rubus chamaemorus*, *Salix* spp., and moss species. The mixed deciduous and white spruce stands had greater average canopy cover than the black spruce sites (56 % in mixed deciduous-spruce sites and 17 % in black spruce sites) and greater abundances of native flowers (approx. 1.8 times the number of flowers per m²).

Experimental design

In 2011, we selected 17 sites placed greater than 300 m apart to minimize pollinator movement between sites. Nine sites were in mixed deciduous and spruce sites and eight were in black spruce forest sites. Sites were circular and extended 40 m in all directions from the site center. *M. albus* did not occur at any of these sites. Eleven sites were randomly assigned to have 40 greenhouse-grown flowering second year *Melilotus albus* plants added to the site center (designated “Mel 40”), and six were control sites (no *M. albus* added). The sites contained one or both of the focal native species, with 16 sites containing *V. vitis-idaea* and 15 sites containing *R. groenlandicum* (Table 2.1).

In 2012, we discontinued the site that did not have *V. vitis-idaea* and added two new sites to bring the total number of sites to 18. To address the influence of invasive plant patch size on the reproductive success of our focal species, we added a higher *M. albus* addition level to our design in 2012 (120 plants added, designated “Mel 120”). The eighteen sites were allocated to each of the three treatment levels: control, Mel 40, and Mel 120 (six sites each). To compare years directly, we retained the same treatments in six of the sites (three control and three Mel 40 sites). The remaining three control sites, three Mel 40 sites and six Mel 120 sites were randomly assigned. We assigned sites without respect to habitat type, but had multiple sites of each treatment in each with the exception of a single black spruce site that received the Mel 120 treatment (Table 2.1).

M. albus was added to the Mel 40 or Mel 120 sites at the time that *V. vitis-idaea* and *R. groenlandicum* flower buds emerged, but had not yet opened. *M. albus* were grown in the greenhouse in “conetainer” pots (7 cm diameter at the top, 22 cm in length); each pot contained one individual with 5 to 181 inflorescences (mean of 49 ± 18 flowers per inflorescence). Either 40 or 120 pots were placed in the center of the site in holes of similar dimensions so that the top of the pot was flush with the ground surface. *M. albus* density was 15 plants per m², resulting in circular patches approximately 2.6 m² and 8 m² in size. The range in number of inflorescences added to each site was 334 to 942 (16,366 to 46,158 total flowers) for Mel 40 sites and 1068 to 1608 (52,332 to 78,792 total flowers) for Mel 120 sites. The addition levels we used (Mel 40 and Mel 120) were comparable to the patch sizes found within burned boreal forest in interior Alaska, which are typically in the earliest of invasion stages where they occur (Villano and Mulder 2008). Once flowers of focal native species had dropped their petals (18-28 days after *M. albus* addition), *M. albus* was removed from the sites. To prevent accidental introductions, we

removed any immature seeds that appeared on the *M. albus* plants throughout the duration of the experiment. Sites were also visited a year following the experiments to confirm that no *M. albus* plants were present.

Within each site, 25 circular plots were established for each of the occurring focal species (1 m² plot for *V. vitis-idaea*, and 1.77 m² plot for *R. groenlandicum*) ranging from 1 m to 40 m from the site center. Five plots were placed within five distance ranges from the site center: 1 to 2 m, 3 to 5 m, 8 to 10 m, 15 to 20 m, and 25 to 40 m. Within these plots, five *V. vitis-idaea* or five *R. groenlandicum* ramets were marked for tracking fruit set and seed production. In the 1 to 2 m distance category, focal plants were always selected outside of the *M. albus* patch to avoid plants where the root systems may have been damaged during the *M. albus* transplanting. This study focuses on whole-site impacts of *M. albus* on focal native species reproduction, and spatial variation of the effects within sites will be discussed in a forthcoming paper. We initially attempted to include *Vaccinium uliginosum* as a third focal species, however this species flowered prior to the outplanting of *M. albus* and we were only able to collect limited data from this species in the first year and therefore the results are not presented here. Results from our year of data collection on *V. uliginosum* are presented in Appendix 2.1.

Pollinator activity and community

In 2011, we observed insect pollinator activity in 15 of the 17 sites (four control sites and 11 Mel 40 sites). We did not observe pollinator activity in 2012. Pollinator observations occurred between 8 am and 6 pm during calm, rain-free periods from June 6 to 18 in 2011. One focal plot per distance category was randomly chosen for a 2 m × 2 m pollinator observation of 15 minutes, for a total of five observations per site. For each observation, we counted the total number of open flowers and then recorded pollinator landings on open flowers of focal species within the

plot. Observed pollinators were grouped into categories (butterflies, wasps, bumblebees, solitary bees, syrphid flies, and non-syrphid flies) for field identification. We calculated visitation rates using insect landings per number of flowers per hour of observation in each plot within each of the 15 sites used for observations (12 sites with *V. vitis-idaea* present and 14 sites with *R. groenlandicum* present). We used four pairs of sites (the four control sites each paired with a Mel 40 site that was observed on the same day) to assess differences in the pollinator community composition between the treatments. Due to overall low number of pollinator sightings in these sites, we pooled observations in the four control sites and the four Mel 40 sites to calculate Simpson's diversity index and proportional similarity (Brower and Zar 1984).

Pollination

To measure pollen deposition, we collected *V. vitis-idaea* and *R. groenlandicum* stigmas from randomly selected open flowers near each of our marked focal plants. We did not take stigmas from marked plants to avoid interfering with fruit set. Three (in 2011) or five (in 2012) *V. vitis-idaea* and five *R. groenlandicum* stigmas were collected from each of the 25 plots in each site approximately 14 days after the *M. albus* was added. The stigmas were mounted on microscope slides and stained with a basic fuchsin gel (Kearns and Inouye 1993). Each pollen grain or tetrad (in the case of *R. groenlandicum* and *V. vitis-idaea* pollen) on the stigma was identified to genus (using anther vouchers we collected from all flowering species at the sites as a reference) and counted under a compound light microscope. Proportion of heterospecific pollen grains on the stigmas was low (3.2 ± 0.3 % for *V. vitis-idaea* and 0.8 ± 0.2 % for *R. groenlandicum*), so only conspecific pollen loads on the stigmas were used in the final analysis. Flowers were considered to be “well-pollinated” when they had ≥ 10 pollen tetrads on the stigma. We selected this threshold because fruit production increases sharply at this pollen level

for both focal species in control plots (data not shown). Few stigmas had zero pollen grains on them, making presence or absence of pollen inadequate to detect variation in proportion of flowers that were pollinated.

Fruit set and seed production

We calculated percent fruit set as the percentage of flower buds on marked plants at the beginning of our experiment that produced fruit by the end of the growing season. To determine seed production per fruit in *V. vitis-idaea* we dissected up to five berries per marked plant and counted the number of seeds produced under a dissecting microscope. For *R. groenlandicum*, which has minute seeds that are released as the fruit ages and dries, we dried inflorescences at 65 °C until the fruits opened and released the seeds. The weight of the seeds was divided by the number of fruits on the inflorescences to derive seed mass per fruit.

Environmental covariates

We measured biotic and abiotic variables that we expected to influence our response variables. Temperature and relative humidity during the experimental period (time of *M. albus* addition to time of *M. albus* removal in the site or nearest *M. albus* addition site for control sites) were obtained every 30 min using a HOBO-Pro data logger (Onset Computer, Cape Cod, Massachusetts, USA) fixed 0.5 m above the ground surface at the center of each site. Number of hours of rain was estimated as number of hours with $RH \geq 100\%$. Tree canopy cover was estimated for each of the 25 plots using a convex spherical crown densiometer (Model A; Forest Densiometers, Bartlesville, Oklahoma, USA) on the north and south edges of the plot. We visually estimated the percent shrub cover present above the *V. vitis-idaea* (up to 1 m in height) in each plot. *R. groenlandicum* was the tallest understory plant in the plots where it occurred, so shrub cover over this species was not a factor. To provide an estimate of flower abundance and

richness, we counted the number of open flowers and flower buds present for each insect-pollinated species within the 25 plots at the time of *M. albus* addition.

Analysis

To look for differences in pollinator visitation rates between control and Mel 40 treatments, we used a non-parametric Wilcoxon rank sum test on site level averages. All our other response variables were calculated as averages of 25 focal plant plots per site and met the assumptions of normality and constant variance. We performed the statistical analyses on the plant and environmental data using SAS v.9.1 (SAS Institute, Cary, North Carolina) and the pollinator data using R v. 2.14.2 (R Development Core Team 2012).

To determine the influence of the *M. albus* addition treatment and year on *V. vitis-idaea* and *R. groenlandicum* pollination, fruit set and seed production, we conducted MANOVA using site-level means of response variables for *V. vitis-idaea* and *R. groenlandicum*. The response variables in the multivariate models included number of conspecific pollen grains delivered to stigmas (“conspecific pollen”), percent flowers receiving ≥ 10 pollen grains or tetrads (“% pollinated flowers”), % flowers setting fruit (“% fruit set”), and number of seeds per fruit for *V. vitis-idaea* or seed mass per fruit for *R. groenlandicum* (“seeds or seed mass per fruit”). We conducted several tests to disentangle treatment, year and site effects. We first tested for a treatment effect in each year individually. We then tested for year, treatment, and year by treatment interactions using both years but excluding the sites that received the Mel 120 treatment in 2012 (since this treatment was not imposed in 2011). Finally, we evaluated site and year effects using only sites where the treatment remained the same across both years of the experiment. Separate ANOVAs were then run to assess which individual response variable responded most strongly to treatment and year effects, and to allow us to disentangle the relative

roles of pollen limitation and resource limitation on our focal species' reproductive responses. We took a conservative approach to interpreting these ANOVA results to reduce risk of committing type I error and used Bonferroni-corrected p -values. We also treated the abundance of *M. albus* inflorescences added to each site as a continuous variable and used linear regression to determine if the number of *M. albus* inflorescences present influenced our four pollination and reproduction response variables.

To identify the relative importance of *M. albus* and the other environmental variables in explaining differences in pollination, fruit set, and seed production between sites, we calculated Akaike's Information Criterion variable importance values for seven or eight site-level abiotic and biotic covariates using multiple linear regression on the four response variables for each of the focal species. The covariates included the number of *M. albus* inflorescences added to site, percent tree canopy cover per plot, percent shrub cover per plot (for *V. vitis-idaea* only), number of conspecific flowers per plot, number of all flowers per plot, flower richness per plot, and mean temperature and number of hours of rain during the addition experiment at the site. We included all additive models and ranked them using Akaike's Information Criterion adjusted for small sample size (AIC_c ; Burnham and Anderson 2002), then calculated cumulative AIC_c weights ($0 \leq \sum \omega_i \leq 1$), or "importance values," for each biotic or abiotic variable (Burnham and Anderson 2002; Arnold 2010). We considered importance values > 0.55 as indicative of well-supported variables. Average parameter estimates for each well-supported variable were calculated using the set of best-supported models (those within 2 AIC_c units of the model with the lowest AIC_c score) to assess the direction of the response of each focal species to the parameter. Since canopy cover differed greatly between mixed deciduous-spruce sites and black spruce sites, and it had an important positive relationship with pollination and seed production

variables in *V. vitis-idaea* (Table 2.4), we re-ran the multiple linear regression analysis described above separately for the two habitat types to determine the relative importance of *M. albus* in the two habitat types.

Results

Effects of M. albus on pollinator activity and community

V. vitis-idaea - All sites without *M. albus* had no pollinator visitation, while Mel 40 treatment sites had a range of visitation rates between 0 visits/flower/hour and 0.46 visits/flower/hour (Fig. 2.2a). The mean visitation rate to control sites was 0 visits/flower/hour, while the mean at Mel 40 treatment sites was 0.11 visits/flower/hour. This effect was not statistically significant ($W = 10, p = 0.22$).

R. groenlandicum - Three out of four control sites without *M. albus* had no pollinator visitation to *R. groenlandicum*, while Mel 40 treatment sites had a range of visitation rates between 0 visits/flower/hour and 0.034 visits/flower/hour (Fig. 2.2b). The mean visitation rate to control sites was 0.0006 visits/flower-hour, while the mean at Mel 40 treatment sites was 0.0076 visits/flower/hour. These means did not significantly differ from each other ($W = 15, p = 0.46$).

Pollinator community - The pollinator guilds had 40% proportional similarity between the pooled control and Mel 40 site pairs. More pollinator guilds visited the focal species in the Mel 40 sites than control sites. Butterflies, syrphid flies, other types of flies, and wasps were only present in the Mel 40 treatment sites, while bumblebees and solitary bees were present in control and Mel 40 sites. The pollinator guild-level Simpson's D was 0.49 in the control sites and 0.77 in the Mel 40 sites.

Effects of M. albus on native plant pollination and reproduction

V. vitis-idaea- In our MANOVA, we found a marginal treatment effect on *V. vitis-idaea*

pollination and reproduction in 2012, and a marginal year effect (Table 2.2). In 2012, Mel 120 sites produced 4 more seeds per berry on average compared to the control and Mel 40 sites, a significant increase of approximately 15% (Table 2.3, Fig. 2.3d). Fruit set in 2012 was greater than in 2011 for *V. vitis-idaea* (Table 2.3, Fig. 2.3c) and the magnitude of difference in fruit set in Mel 40 compared to control sites was greater in 2012 than in 2011 (1.1% increase in 2011, 13.4% increase in 2012, $F = 5.26$, $p = 0.03$; Fig. 2.3c). We did not detect any differences in the number conspecific pollen grains on *V. vitis-idaea* stigmas or the percent well-pollinated flowers between treatments or between years in our ANOVA tests (Table 2.3, Fig. 2.3a,b). The number of conspecific pollen grains on stigmas, percent flowers pollinated, fruit set, and seeds per berry in *V. vitis-idaea* could not be explained by the number of *M. albus* inflorescences in the site (Table 2.4).

R. groenlandicum- We found a highly significant year effect for our *R. groenlandicum* MANOVA model testing for year, treatment, and interaction effects (Table 2.2). Seed mass per fruit was the individual variable driving this response (Table 2.3). There was more than double the mean seed mass per fruit in 2012 compared to 2011 (Fig. 2.4d). In 2011, Mel 40 sites had 42% greater seed mass per fruit relative to the control sites, while in 2012 the Mel 40 sites had 24% less seed mass per fruit relative to the control sites (Fig. 2.4d). The number of *M. albus* inflorescences at a site decreased the number of *R. groenlandicum* pollen tetrads and percent flowers pollinated (a decrease of one tetrad or 1% flowers pollinated for every 100 inflorescences added; Table 2.4). Fruit set could not be explained by the *M. albus* treatment level in either year (Table 2.3, Fig. 2.4c), nor could it be explained by the number of *M. albus* inflorescences at the site (Table 2.4).

Relative importance of M. albus and environmental factors in predicting reproduction

V. vitis-idaea- The number of *M. albus* inflorescences, canopy cover, flower richness, and mean temperature were identified as important in explaining the variation among sites in percent *V. vitis-idaea* flowers pollinated (Table 2.5). *M. albus* had a lower cumulative parameter weight compared to the other three variables, all three of which were positively related to % flowers pollinated (Table 2.5). *M. albus* inflorescence number was important in explaining % *V. vitis-idaea* flowers pollinated in black spruce sites, but not in mixed deciduous and white spruce sites (Table 2.6). The number of *M. albus* inflorescences was not identified as being as important as the other environmental variables for any of the other three *V. vitis-idaea* response variables across all sites (Table 2.5) or in the two different habitat types.

R. groenlandicum- The number of *M. albus* inflorescences at a site outweighed the importance of all the other vegetation and weather variables in explaining conspecific pollen loads and the percent pollinated *R. groenlandicum* flowers (Table 2.5). *R. groenlandicum* fruit set, however, was better explained by canopy cover, flower richness, and hours of rain, which were all negatively related to fruit set (Table 2.5). The *R. groenlandicum* seed mass per fruit was best explained by the percent canopy cover and average temperature at the sites, both of which had positive relationships with the seed mass per fruit (Table 2.5). The number of *M. albus* inflorescences was not identified as important in explaining the response variables when we divided the sites by habitat type.

Discussion

The existing body of literature addressing the effects of invasive plants on native plant pollination and reproduction has documented a diversity of competitive (Chittka and Schürkens 2001; Brown et al. 2002; Kandori et al. 2009; Flanagan et al. 2010), facilitative (Nielsen et al.

2008; Tepedino et al. 2008; Da Silva et al. 2013) and neutral effects (Bartomeus et al. 2008a). The majority of these studies, however, focus only on the impacts a non-native plant has on the pollination and reproduction of a single native species (Chittka and Schürkens 2001; Brown et al. 2002; Nielsen et al. 2008; Kandori et al. 2009; Flanagan et al. 2010; Da Silva et al. 2013). By investigating multiple native species within the same sites, our study demonstrates that generalizations made from these single species studies do not capture the complexity of invasive plant interactions within a plant community. We found that addition of *M. albus* increased pollinator diversity in our sites and tended to increase pollinator visitation rates to native *V. vitis-idaea* and *R. groenlandicum*. We saw a facilitative effect of *M. albus* on the seed production of *V. vitis-idaea* in 2012 and no strong effect on *R. groenlandicum* reproduction. However, there was a weak competitive effect on *R. groenlandicum* pollen loads and percent flowers pollinated at the highest *M. albus* densities.

Along with other multi-species studies and plant-pollinator network studies (Moragues and Traveset 2005, Jakobsson et al. 2009, Bartomeus et al. 2008b, Albrecht et al. 2014), we suggest that the identity of shared pollinators between specific invasive and native pairs or identity of new pollinators attracted to the invaded sites are likely determining factors in the reproductive responses of native plants. Our study also indicates that site environmental conditions and resource limitations to plant reproduction further complicate the generalizations that can be made from existing corpus of experimental studies on invasive plant impact on native plant reproduction. We discuss here how both pollinator identity and site environmental conditions may have influenced our results.

***M. albus* effect on pollination and reproduction of two boreal shrubs**

The addition of *M. albus* did little to change pollen loads or pollination rates of *V. vitis-idaea*. Seed production per berry, however, did increase in the presence of the highest *M. albus* abundance level. A higher seed set without evidence of higher pollen loads suggests that there is an increase in the proportion of outcross pollen being delivered by pollinators when higher densities of *M. albus* are introduced. This explanation is consistent with previous hand-pollination experiments in which cross-pollinated *V. vitis-idaea* plants produced more seeds than self-pollinated plants (Jacquemart and Thompson 1996; Fröborg 1996; Jacquemart 1997), but did not have higher fruit set (Jacquemart and Thompson 1996; Jacquemart 1997).

The shift in the pollinator community composition in the presence of *M. albus* provides a mechanism through which the outcrossing rates may change. Densely-flowered clonal plants like *V. vitis-idaea* are subject to high levels of within genet pollen transfer due to the foraging strategies of bumblebees in particular (Jacquemart and Thompson 1996). Other pollinating guilds such as butterflies tend to take longer flights between plants than *Bombus* spp. (Proctor et al. 1996) thereby increasing outcross potential. Butterflies, syrphid flies, other flies, and wasps were observed visiting the native focal species only at sites where *M. albus* was added. Other studies have documented changes in pollinator behaviors (e.g., changes in distance traveled between plants) as a result of non-native plant invasions (Ghazoul 2004), which could also explain a possible shift in outcrossing rates.

The modest decline in conspecific pollen loads and pollination rates of *R. groenlandicum* flowers with greater numbers of *M. albus* flowers is suggestive of a greater overlap in pollinator community and a shift by more effective *R. groenlandicum* pollinators to visiting *M. albus* when it is at high densities. Indeed a high proportion of pollinator guilds are shared between *R. groenlandicum* and *M. albus* (plant-pollinator networks are explored in Schneller et al., in prep).

Despite a potential for reduced conspecific pollen flow, we did not observe an associated decline in fruit or seed set. Resource limitation is likely to play a major role in limiting sexual reproduction in these boreal communities (Grainger and Turkington 2013) and pollination rates beyond a minimum threshold may not result in changes in fruit and seed set.

The magnitude of the *M. albus* effect on *V. vitis-idaea* fruit set and *R. groenlandicum* seed mass per fruit was greater in 2012 compared to 2011. In 2011 it rained for almost twice as many hours as in 2012 (173 vs. 97 hours during the experimental period), which likely allowed for a greater amount of time for pollinator activity in the second year (Kuchko 1988; Tuell and Isaacs 2010). It may have also affected which types of pollinators are active (Corbett et al. 1993). Other studies have found it difficult to disentangle the role of variations in weather in *V. vitis-idaea* fruit set (Jacquemart 1997; Krebs et al. 2009), with factors like late spring frosts having a potential effect on both flowers and insect populations. Similarly, we cannot determine whether the warmer conditions in the second year of our study reduced pollinator limitation or resources limitation for *V. vitis-idaea* fruit set and *R. groenlandicum* seed production. *V. vitis-idaea* fruit set was negatively related to the number of heterospecific flowers and positively related to the number of conspecific flowers, which is consistent with pollen limitation. Further, seed production for *V. vitis-idaea* increased only under the highest level of *M. albus* addition, suggesting that this variable is pollinator limited in a warm year.

Relative importance of M. albus and environmental variables in explaining reproduction

M. albus inflorescence number was more important for explaining *R. groenlandicum* pollination than were the other biotic and abiotic variables we measured. The importance of *M. albus* did not persist in subsequent *R. groenlandicum* reproduction. Similarly, the number of *M. albus* inflorescences was only important in explaining the percent flowers pollinated for *V. vitis-*

idaea, while fruit set was more influenced by the environmental conditions. This finding is consistent with Totland et al. (2006), who documented non-native *Phacelia tanacetifolia* affecting pollinator visitation to a native boreal plant species (*Melampyrum pratense*), but not reproductive success. Totland et al. (2006) similarly attributed this finding to the high resource limitations on reproduction in boreal forest habitats.

Our finding that *M. albus* had far greater importance in explaining pollination rates of *V. vitis-idaea* in black spruce sites than in mixed deciduous-spruce sites further supports the important role of resource availability in mediating relationships between invasive and native boreal plant reproduction. Black spruce sites tend to have lower soil temperatures (Viereck et al. 1992) and lower densities of native flowers than the mixed deciduous-spruce sites. The reduced floral resources and the lower temperatures for ground-nesting pollinators likely limits the number of pollinators in black spruce sites, and the addition of *M. albus* may act as a distraction for the already low pollinator levels.

Further considerations

Our results point to a clear need for further research in two areas of invasion biology in the boreal forest in particular: plant-pollinator network studies and experimental studies isolating the influence of pollen limitation and resource limitation in invaded and uninvaded habitats. Both of these types of studies would make major contributions toward understanding the reproductive impact of entomophilous invasive plants in species poor, resource limited boreal plant communities.

Both phenological and spatial aspects of our experiment lead us to pose further questions, as well. First, we added fully flowering *M. albus* to sites where *V. vitis-idaea* and *R. groenlandicum* flowers were on the verge of opening, while typically these focal species begin

flowering several days before *M. albus* in interior Alaska (C.P.H. Mulder and K. V. Spellman, unpublished data). The flowering sequence can have large impacts on connections within plant-pollinator networks (Olesen et al. 2008) and may have altered the influence *M. albus* had on our pollination response variables. Our experiment also forced *M. albus* to overlap the full flowering periods of both the native focal species to get an understanding of the maximum potential interaction. In reality, the timing of flowering and length of flowering overlap between the species varies in different years, and the extent of the overlap is likely to play an important role in determining the effects *M. albus* has on *V. vitis-idaea* and *R. groenlandicum* pollination and reproduction.

At the scale we studied (40 m radius sites) we found a positive effect on seeds per fruit in *V. vitis-idaea* and weak negative effect on pollination in *R. groenlandicum*. These results could change if our study scale increased or decreased (Lopezaraiza-Mikel et al. 2007; Jakobsson et al. 2009). With limited pollinator pools in boreal forest and the “pollinator magnet” effect (cf. Lavery 1992) that *M. albus* appears to have in our sites, it is likely that *V. vitis-idaea* near but outside our study sites receive less attention from pollinators of any guild, and that if we expanded our sites the facilitative effect on seeds that we found would disappear. A different net effect may also occur if we had considered sites of a smaller radius around the *M. albus* patch. We will discuss the role of distance from invasive plant patch within our sites in a forthcoming manuscript. These sorts of questions warrant further investigation, particularly in the face of accelerating rates of invasion in boreal forest ecosystems.

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References

- AKEPIC -Alaska Exotic Plant Information Clearing House (2014) AKEPIC Mapping Project Inventory Field Data. University of Alaska Anchorage Alaska Natural Heritage Program and USDA Forest Service, Anchorage, Alaska. Retrieved 9 September 2014 from <http://akweeds.uaa.alaska.edu/>
- Albrecht M, Padrón B, Bartomeus I, Traveset A. 2014. Consequences of plant invasions on compartmentalization and species' roles in plant–pollinator networks. *Proc R Soc B* 281: 20140773. <http://dx.doi.org/10.1098/rspb.2014.0773>
- Arnold TW (2010) Uninformative parameters and model selection using Akaike's Information Criterion. *J Wildl Manag* 74:1175-1178
- Bartomeus I, Bosch J, Vila M (2008a) High invasive pollen transfer, yet low deposition on native stigmas in a *Carpobrotus*-invaded community. *Annals of Botany* 102: 417–424
- Bartomeus I, Vila M, Santamaria L (2008b) Contrasting effects of invasive plants in plant–pollinator networks. *Oecologia* 155: 761-770
- Bartomeus I, Vila M, Steffan-Dewenter I (2010) Combined effects of *Impatiens glandulifera* invasion and landscape structure on native plant pollination. *J Ecol* 98: 440–450
- Brower JE, Zar JH (1984) *Field and Laboratory Methods for General Ecology*, 2nd edn. Wm. C. Brown Publishers, Dubuque, IA
- Brown BJ, Mitchell RJ, Graham SA (2002) Competition for pollination between an invasive species (purple loosestrife) and a native congener. *Ecology* 83:2328–2336
- Burnham KP, Anderson DR (2002) *Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach*, 2nd edn. Springer-Verlag

- Campbell DR (1985) Pollinator sharing and seed set of *Stellaria pubera*: competition for pollination. *Ecology* 66:544–563
- Carlson ML, Shephard M (2007) Is the spread of non-native plants in Alaska accelerating? In: Harrington TB, Reichard SH (eds) *Meeting the challenge: invasive plants in Pacific Northwest ecosystems*, Portland, OR, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, En. Tech. Rep. PNW-GTR-694, pp 111-127
- Carlson ML, Lapina IV, Shephard M, Conn JS, Densmore R, Spencer P, Heys J, Riley J, Nielsen J (2008) Invasiveness ranking system for non-native plants of Alaska. Technical Paper R10-TP-143, USDA Forest Service, Alaska Region, Anchorage, AK.
- Chittka L, Schürkens S (2001) Successful invasion of a floral market. *Nature* 411:653
- Coe HS, Martin JN (1920) Sweet clover seed. Bulletin 844. U.S. Department of Agriculture, Washington, D.C.
- Conn JS, Stockdale CA, Morgan JC (2008a) Characterizing pathways of invasive plant spread to Alaska: propagules from container-grown ornamentals. *Inv Plant Sci Mgmt* 1:331-336
- Conn JS, Beattie KL, Shephard ML, Carlson ML, Lapina I, Hebert M, Gronquist R, Densmore R, Rasy M (2008b) Alaska *Melilotus* invasions: distribution, origin, and susceptibility of plant communities. *Arct Antarct Alp Res* 40:298–308
- Corbet SA, Fussell M, Ake R, Fraser A, Gunson C, Savage A, Smith K (1993) Temperature and the pollinating activity of social bees. *Ecol Entomol* 18: 17-30
- Da Silva EM, King VM, Russell-Mercier JL, Sargent RD (2013) Evidence for pollen limitation of a native plant in invaded communities. *Oecologia* 172:469–476

- Davis AN, Holloway PS, Kruse JJ (2003) Insect visitors and potential pollinators of lingonberries, *Vaccinium vitis-idaea* subsp. *minus*, in sub-arctic Alaska. *Acta Horti* 626:441-446
- Davis AN (2002) Pollination biology of the lingonberry, *Vaccinium vitis-idaea* subsp. *minus* L. Master's Thesis. University of Alaska Fairbanks, Fairbanks, Alaska.
- Dlusski GM, Glazunova KP, Perfilieva KS (2005) Mechanisms that limit pollinator range in Ericaceae. *Zhurnal Obshchei Biologii* 66:224-238
- Eckardt N (1987) Element stewardship abstract for *Melilotus alba* – sweetclover or white sweetclover, *Melilotus officinalis* – yellow sweetclover. The Nature Conservancy, Minneapolis
- Flanagan RJ, Mitchell RJ, Karron JD (2010) Increased relative abundance of an invasive competitor for pollination, *Lythrum salicaria*, reduces seed number in *Mimulus ringens*. *Oecologia* 164:445–454
- Flanagan RJ, Mitchell RJ, Knutowski D, Karron JD (2009) Interspecific pollinator movements reduce pollen deposition and seed production in *Mimulus ringens* (Phrymaceae). *Am J Botany* 96:809–815
- Fröberg, H. (1996) Pollination and seed production in five boreal species of *Vaccinium* and *Andromeda* (Ericaceae). *Can J Bot* 74:1363-1368
- Garibaldi A (1999) Medicinal flora of the Alaska Natives. University of Alaska Anchorage Press, Anchorage, AK.
- Gathmann A, Tscharrntke T (2002) Foraging ranges of solitary bees. *J Anim Ecol* 71: 757–764
- Ghazoul J (2004) Alien abduction: disruption of native plant pollinator interactions by invasive species. *Biotropica* 36:156–164

- Grainger TN, Turkington R (2013) Long-term nutrient enrichment differentially affects investment in sexual reproduction in four boreal forest understory species. *Plant Ecol* 214:1017–1026
- Hall IV, Beil CE (1970) Seed germination, pollination, and growth of *Vaccinium vitis-idaea* var. *minus* Lodd. *Can J Plant Sci* 50:731-732
- Holloway PS (2006) Managing wild bog blueberry, lingonberry, cloudberry, and crowberry stands in Alaska. Report for University of Alaska Fairbanks and Natural Resource Conservation Service, Fairbanks, AK
- Hultén E (1968) Flora of Alaska and Neighboring Territories. Stanford University Press, Stanford, CA.
- Irwin DL (1945) Forty-seven years of experimental work with grasses and legumes in Alaska. College, Alaska: University of Alaska Agricultural Experiment Station Bulletin, 12: 47
- Jacquemart AL (1997) Pollen limitation three sympatric species of *Vaccinium* (Ericaceae) in the Upper Ardennes, Belgium. *Plant Syst Evol* 207:159-172
- Jacquemart AL, Thompson JD (1996) Floral and pollination biology of three sympatric *Vaccinium* (Ericaceae) species in the upper Ardennes, Belgium. *Can J Bot* 74:210-221
- Jakobsson A, Padrón B, Traveset A (2009) Competition for pollinators between invasive and native plants: effects of spatial scale of investigation (note). *Ecoscience* 16:138-141
- Kandori I, Hirao T, Matsunaga S, Kurosaki T (2009) An invasive dandelion unilaterally reduces the reproduction of a native congener through competition for pollination. *Oecologia* 159:559–569
- Kearns CA, Inouye DW (1993) Techniques for pollination biologists. University Press of Colorado. Niwot, Colorado.

- Kevan PG, Tikhmenev EA, Usui M (1993) Insects and plants in the pollination ecology of the boreal zone. *Ecol Res* 8:247–267
- Krebs CJ, Boonstra R, Cowcill K, Kenney AJ (2009) Climatic determinants of berry crops in the boreal forest of the southwestern Yukon. *Botany* 87:401–408
- Kuchko AA (1988) Bilberry and cranberry yields and the factors controlling them in the forests of Karelia USSR. *Acta Bot Fennica* 136: 23-25
- Laverty TM (1992) Plant interactions for pollinator visits: a test of the magnet species effect. *Oecologia* 89: 502–508
- Lopezaraiza-Mikel ME, Hayes RB, Whalley MR, Memmott J (2007) The impact of an alien plant on a native plant-pollinator network: an experimental approach. *Ecology Letters* 10:539–550
- Malacalza NH, Caccavari MA, Fagúndez G, Lupano CE (2005) Unifloral honeys of the province of Buenos Aires, Argentina. *J Sci Food Agric* 85:1389–1396 (2005)
- Molina-Montenegro MA, Badano EI, Cavieres LA (2008) Positive interactions among plant species for pollinator service: assessing the ‘magnet species’ concept with invasive species. *Oikos* 117: 1833-1839
- Moragues E, Traveset A (2005) Effect of *Carpobrotus* spp. on the pollination success of native plant species of the Balearic Islands. *Biol Conserv* 122: 611–619
- Morales CL, Traveset A (2008) Interspecific pollen transfer: magnitude, prevalence and consequences for plant fitness. *Crit Rev Plant Sci* 27:221-238
- Muñoz AA and Cavieres LA (2008) The presence of a showy invasive plant disrupts pollinator service and reproductive output in native alpine species only at high densities. *J Ecol* 96:459–67

- Myneni RB, Keeling CD, Tucker CJ, Asrar G, Nemani RR (1997) Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* 386: 698-702
- Nielsen C, Heimes C, Kollmann J (2008) Little evidence for negative effects of an invasive alien plant on pollinator services. *Biol Invasions* 10:1353–1363.
- Nelson JL, Zavaleta E, Chapin FS III (2008) Boreal fire effects on subsistence resources: landscape diversity as a critical component of rural livelihoods in Alaska and adjacent Canada. *Ecosystems* 11:156-171
- Olesen JM, Bascompte J, Elberling H, Jordano P (2008) Temporal dynamics in a pollination network. *Ecology* 89:1573-1582
- Peterson SF (1989) Beekeeping under the northern lights. *American Bee Journal* 129:33-35
- Proctor M, Yeo P, Lack A (1996) The natural history of pollination. Timber Press, Portland
- Quiner M (2005) Ranchers get the blues: area citizens consider branching out into berries. Peninsula Clarion, October 11, 2005, <http://www.peninsulaclarion.com/stories/101105/>
- R Development Core Team (2012). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN. 3-900051-07-0, URL <http://www.R-project.org/>
- Royer F, Dickinson R (1999) Weeds of the Northern U.S. and Canada. The University of Alberta Press, Edmonton, Alberta
- Sanderson LA, McLaughlin JA, Antunes PM (2012) The last great forest: a review of the status of invasive species in the North American boreal forest. *Forestry* 85: 329-339
- Serreze MC, Walsh JE, Chapin FS III, Osterkamp T, Dyurgerov M, Oechel WC, Romanovsky V, Morison J, Zhang T, Barry RG (2000) Observational evidence of recent change in the northern high latitude environment. *Clim Change* 46:159–207

- Shugart HH, Leemans R, Bonan GB (1992) A systems analysis of the boreal forest. Cambridge University Press, Cambridge
- Spellman BT, Wurtz T (2011) Invasive white sweetclover (*Melilotus officinalis*) impacts native recruitment along rivers in interior Alaska. *Biol Invasions* 13:1779–1790
- Spellman KV, Mulder CPH, Hollingsworth TN (2014) Susceptibility of burned black spruce (*Picea mariana*) forests to non-native plant invasions in Interior Alaska. *Biol Invasions* 16:1879–1895
- Tepedino VJ, Bradley BA, Griswold TL (2008) Might flowers of invasive plants increase native bee carrying capacity? Intimations from Capitol Reef National Park, Utah. *Nat Area J* 28:44–50
- Totland Ø, Nielsen A, Bjerknes AL, Ohlson M (2006) Effects of an exotic plant and habitat disturbance on pollinator visitation and reproduction in a boreal forest herb. *Am J Bot* 93:868–873
- Tuell JK, Isaacs R (2010) Weather during bloom affects pollination and yield of highbush blueberry. *J Econ Entomol* 103:557–562
- Turkington RA, Cavers PB, Rempel E (1978) The biology of Canadian weeds. 29. *Melilotus alba* Desr. and *M. officinalis* (L.) Lam. *Can J Plant Sci* 58:523–537
- U.S. Census 2010. Census 2010 Data for the State of Alaska. U.S. Census Bureau.
<http://www.census.gov/census2010/states/ak.html>
- Viereck LA, Dyrness CT, Batten AR, Wenzlick KJ (1992) The Alaska vegetation classification. Gen. Tech. Rep. PNW-GTR-286. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. Portland, Oregon.

- Villano KL, Mulder CPH (2008) Invasive plant spread in burned lands of interior Alaska. Technical report for National Park Service-Alaska Region and National Aeronautics and Space Administration, Fairbanks, Alaska
- Walker DA, Walker MD (1991) History and pattern of disturbance in Alaskan arctic terrestrial ecosystems: a hierarchical approach to analysing landscape change. *J Appl Ecol* 28:244-276
- Waser NM (1978) Competition for pollination and sequential flowering in two Colorado wildflowers. *Ecology* 59:934–944
- Waser NM (1983) Competition for pollination and floral character differences among sympatric plant species: a review of evidence. In: Jones CE, Little RJ (eds) *Handbook of experimental pollination biology*. Van Nostrand Reinhold, New York, pp 277–293
- Westphal C, Steffan-Dewenter I, Tschardt T (2003) Mass-flowering crops enhance pollinator densities at a landscape scale. *Ecol Letters* 6: 961–965
- Westrich P (1996) Habitat requirements of central European bees and the problems of partial habitats. In: Matheson A, Buchmann SL, O’Toole C, Westrich P, Williams H (eds) *The Conservation of Bees*. Linnaean Society of London and the International Bee Research Association, Academic Press, London, UK, pp. 1–16
- Wheelwright NT, Dukeshire EE, Fontaine JB, Gutow SH, Moeller DA, Schuetz JG, Smith TM, Rodgers SL, Zink AG (2006) Pollinator limitation, autogamy and minimal inbreeding depression in insect-pollinated plants on a boreal island. *Am Midl Nat* 155: 19-38

Table 2.1 Number of sites for each species and in different habitat types in 2011 and 2012 by treatment.

Species	Habitat type	Year and Treatment				
		2011		2012		
		Control	Mel 40	Control	Mel 40	Mel 120
<i>V. vitis-idaea</i>	Mixed	4	5	4	2	5
	Black spruce	2	5	2	4	1
	<i>Total</i>	6	10	6	6	6
<i>R. groenlandicum</i>	Mixed	2	5	2	2	3
	Black spruce	2	6	2	4	1
	<i>Total</i>	4	11	4	6	4

Table 2.2 MANOVA results for models testing for *M. albus* addition treatment (trt), year, site and interaction effects for the combination of four response variables (total pollen on stigmas, percent flowers pollinated, percent flowers setting fruit, and number of seeds per fruit for *V. vitis-idaea* or seed mass per fruit for *R. groenlandicum*).

Focal Species	Data set	Source of variation	Wilks' λ	F	num	denom	p
					df	df	
<i>V. vitis-idaea</i>	2011	trt	0.83	0.56	4	11	0.70
	2012	trt	0.37	1.96	8	24	0.10
	2011 & 2012 excluding Mel 120	year	0.66	2.68	4	21	0.06
		trt	0.81	1.27	4	21	0.31
		year*trt	0.92	0.44	4	21	0.78
	Sites where trt remains same in 2011 & 2012	site	0.003	1.72	20	8	0.23
		year	0.03	15.73	4	2	0.06
<i>R. groenlandicum</i>	2011	trt	0.77	0.76	4	10	0.57
	2012	trt	0.51	0.81	8	16	0.61
	2011 & 2012 excluding Mel 120	year	0.23	15.23	4	18	<0.0001
		trt	0.98	0.12	4	18	0.98
		year*trt	0.76	1.45	4	18	0.26
	Sites where trt remains same in 2011 & 2012	site	0.002	1.42	16	4	0.41
		year	0.14	1.51	4	1	0.54

3Table 2.3 ANOVA results for models testing for *M. albus* addition treatment effects for four individual response variables (total pollen on stigmas, percent flowers pollinated, percent flowers setting fruit, and number of seeds per fruit for *V. vitis-idaea* or seed mass per fruit for *R. groenlandicum*).

Table 2.3 ANOVA results for models testing for *M. albus* addition treatment (trt) effects for four individual response variables (total pollen on stigmas, percent flowers pollinated, percent flowers

Focal Species	Data set	Source of variation	df	Error df	Response Variables			
					Conspecific pollen <i>F</i>	% flowers pollinated <i>F</i>	% fruit set <i>F</i>	Seeds or seed mass per fruit <i>F</i>
<i>V. vitis-idaea</i>	2011	trt	1	14	0.01	1.04	0.03	0.13
	2012	trt	2	15	0.27	0.02	1.09	6.30*
	2011 & 2012 excluding Mel 120	year	1	24	0.01	1.20	12.06*	1.77
		trt	1		0.19	0.45	1.59	0.04
		year*trt	1		0.28	0.71	1.39	0.19
	Sites where trt remains same in 2011 & 2012	site	5	5	2.09	0.82	1.39	0.66
		year	1		0.36	0.06	7.67	1.09
<i>R. groenlandicum</i>	2011	trt	1	13	1.15	0.53	0.10	2.02
	2012	trt	2	11	1.30	2.00	0.41	1.53
	2011 & 2012 excluding Mel 120	year	1	21	1.17	1.31	0.12	24.58*
		trt	1		0.35	0.25	0.04	0.13
		year*trt	1		0.54	0.26	0.04	4.57
	Sites where trt remains same in 2011 & 2012	site	4	4	2.50	1.74	7.01	6.88
		year	1		0.00	1.13	0.07	20.55*

setting fruit, and number of seeds per fruit for *V. vitis-idaea* or seed mass per fruit for *R. groenlandicum*). * indicates a Bonferroni- corrected $p < 0.05$.

Table 2.4 Linear regression analysis for *V. vitis-idaea* and *R. groenlandicum* pollination and reproduction responses to the number of *M. albus* inflorescences present at a site. The number of *M. albus* inflorescences present in sites where it was added ranged from 334 to 1608 inflorescences (mean 795 ± 85). Individual *M. albus* plants had up to 181 inflorescences with approximately 50 flowers per inflorescence. Models with $p < 0.1$ are indicated in bold.

Species	Response Variable	model df	error df	<i>M. albus</i> inflorescences parameter estimate (s.e.)		<i>F</i>	<i>p</i>	R ²
<i>V. vitis-idaea</i>	Conspecific pollen	1	34	-0.0002	(0.002)	0.01	0.94	0.0002
	% flowers pollinated	1	34	-0.00003	(0.00005)	0.41	0.52	0.01
	% fruit set	1	34	0.001	(0.006)	0.05	0.82	0.002
	Seeds per fruit	1	34	0.002	(0.002)	2.07	0.16	0.06
<i>R. groenlandicum</i>	Conspecific pollen	1	27	-0.007	(0.003)	3.82	0.06	0.12
	% flowers pollinated	1	27	-0.01	(0.006)	4.05	0.05	0.13
	% fruit set	1	27	-0.005	(0.005)	0.99	0.33	0.04
	Seeds per fruit	1	27	0.0004	(0.002)	0.07	0.79	0.003

Table 2.5 Modeled Akaike's Information Criterion average parameter estimates (\bar{b}) and relative variable importance (cumulative parameter weights; $\sum \omega^i$) for candidate variables explaining differences in total pollen deposited on stigmas, % flowers well pollinated (≥ 10 pollen grains), % flowers setting fruit, and seeds per fruit (total number seeds for *V. vitis-idaea* and seed mass for *R. groenlandicum*) for focal species across all sites. Bold values indicate well-supported variables ($\sum \omega^i > 0.55$) and average parameter values for these variables were taken over models with a difference in AICc < 2 .

Species	Explanatory Variables	Response variables							
		conspecific pollen		% flowers pollinated		% fruit set		Seeds or seed mass per fruit	
		\bar{b}	$\sum \omega^i$	\bar{b}	$\sum \omega^i$	\bar{b}	$\sum \omega^i$	\bar{b}	$\sum \omega^i$
<i>V. vitis-idaea</i>	# <i>M. albus</i> inflorescences	.	0.23	-8 x 10⁻⁵	0.58	.	0.19	.	0.26
	canopy cover (%)	0.12	0.67	0.003	0.86	.	0.28	0.09	0.86
	shrub cover (%)	.	0.42	.	0.33	.	0.30	.	0.35
	# <i>V. vitis-idaea</i> flowers	.	0.26	.	0.39	2.25	0.88	.	0.34
	# all flowers	.	0.26	.	0.40	-2.30	0.90	.	0.30
	flower richness	.	0.41	0.09	0.68	16.45	0.84	3.40	0.72
	avg. temperature	.	0.24	0.06	0.67	.	0.28	.	0.40
	hours of rain	.	0.24	.	0.22	-0.13	0.86	.	0.23
<i>R. groenlandicum</i>	# <i>M. albus</i> inflorescences	-0.01	0.68	-0.01	0.71	.	0.54	.	0.19
	canopy cover (%)	.	0.24	.	0.25	-0.31	0.99	7 x 10⁻⁶	0.83
	# <i>R. groenlandicum</i> infloresc.	.	0.22	.	0.23	.	0.21	.	0.28
	# all flowers	.	0.24	.	0.24	.	0.23	.	0.20
	flower richness	.	0.30	.	0.23	-5.93	0.71	.	0.20
	avg. temperature	.	0.32	.	0.36	.	0.31	3 x 10⁻⁴	0.91
	hours of rain	.	0.29	.	0.24	-0.04	0.56	.	0.40

Table 2.6 Average Akaike's Information Criterion parameter estimates (b) and cumulative parameter weights ($\sum \omega^i$) for candidate variables explaining differences in *Vaccinium vitis-idaea* percent flowers well-pollinated (> 10 pollen grains) in mixed deciduous-spruce and black spruce sites. Bold values indicate well-supported variables ($\sum \omega^i > 0.55$), and average parameter values for these variables were taken over models with a difference in $AIC_c < 2$.

Explanatory Variables	Mixed Deciduous-Spruce Sites		Black Spruce Sites	
	b	$\sum \omega^i$	b	$\sum \omega^i$
# <i>M. albus</i> inflorescences	.	0.17	-0.0001	0.60
canopy cover (%)	0.004	0.75	.	0.13
shrub cover (%)	.	0.39	.	0.13
# <i>V. vitis-idaea</i> flowers	.	0.28	.	0.15
# all flowers	.	0.28	.	0.14
flower richness	.	0.36	.	0.17
avg. temperature	.	0.30	0.11	0.94
hours of rain	.	0.28	.	0.19

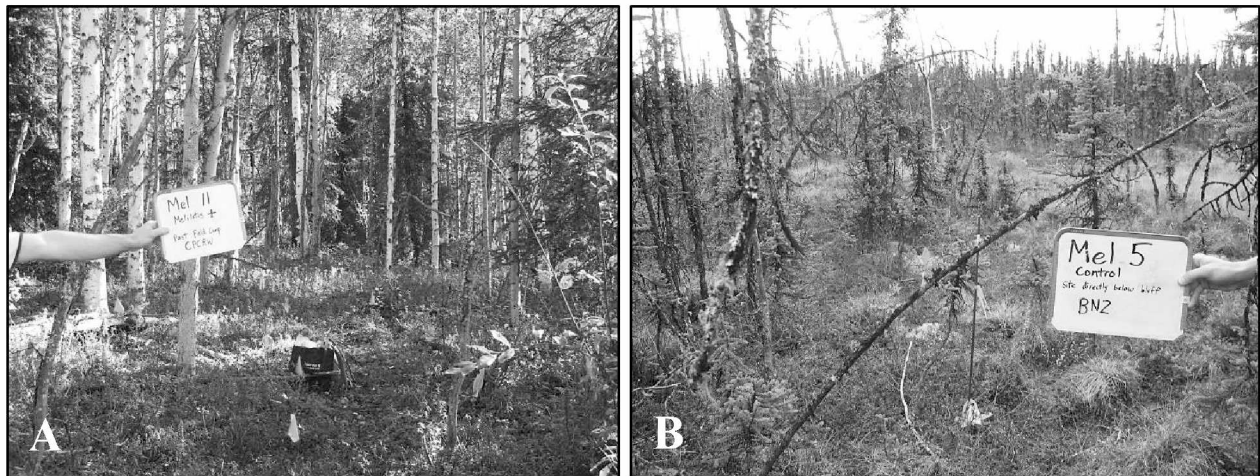


Figure 2.1 Experimental sites were established in two boreal forest habitat types: “mixed” sites that contain deciduous tree species (*Betula neoalaskana* Sarg. and/or *Populus tremuloides* Michx.) and white spruce (*Picea glauca* (Moench) Voss) (A) and black spruce (*Picea mariana* Mill.) sites (B).

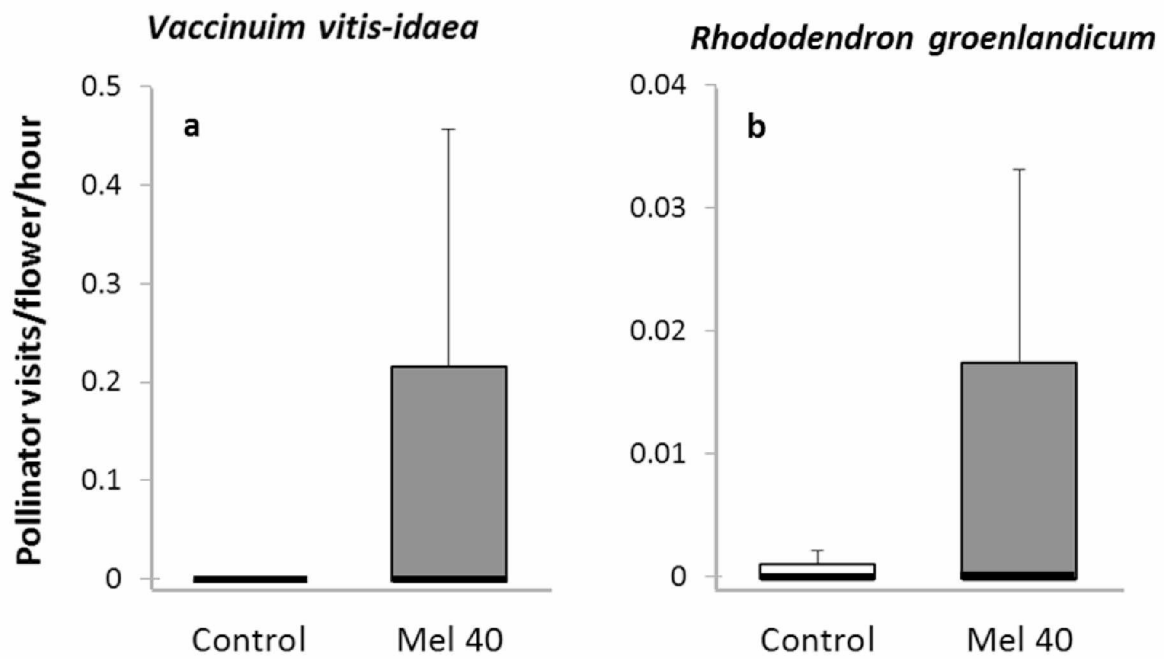


Figure 2.2 Pollinator visitation rates to *V. vitis-idaea* (A) and *R. groenlandicum* (B) flowers in sites without *M. albus* added (control) and in sites with 40 *M. albus* plants added (Mel 40). Each box plot shows the 1st quartile, median (dark line), and 3rd quartile, and whiskers show the minimum and maximum value range for pollinator visitation rates. Minimum, 1st quartile, and median values were equal to 0 in all cases.

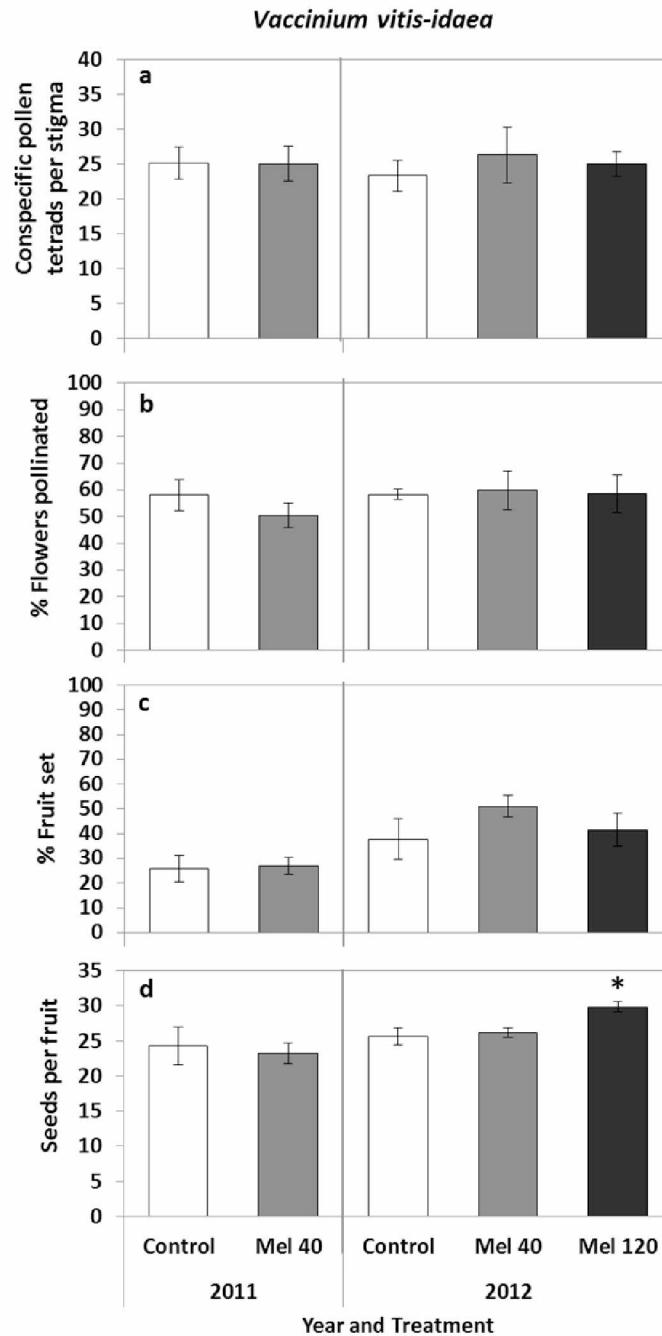


Figure 2.3 *Vaccinium vitis-idaea* conspecific pollen loads on stigmas (A), percent flowers pollinated (B), percent flowers setting fruit (C), and number of seeds per fruit (D) in sites without *Melilotus albus* (control) and sites with 40 or 120 *M. albus* plants added (Mel 40 and Mel 120) during the summers of 2011 and 2012. Bars are mean \pm s.e. of site-level averages for each treatment in each year. The Mel 120 treatment was only conducted in 2012. Differences between treatment means with $p < 0.05$ are indicated by *, and $p < 0.1$ are indicated by +.

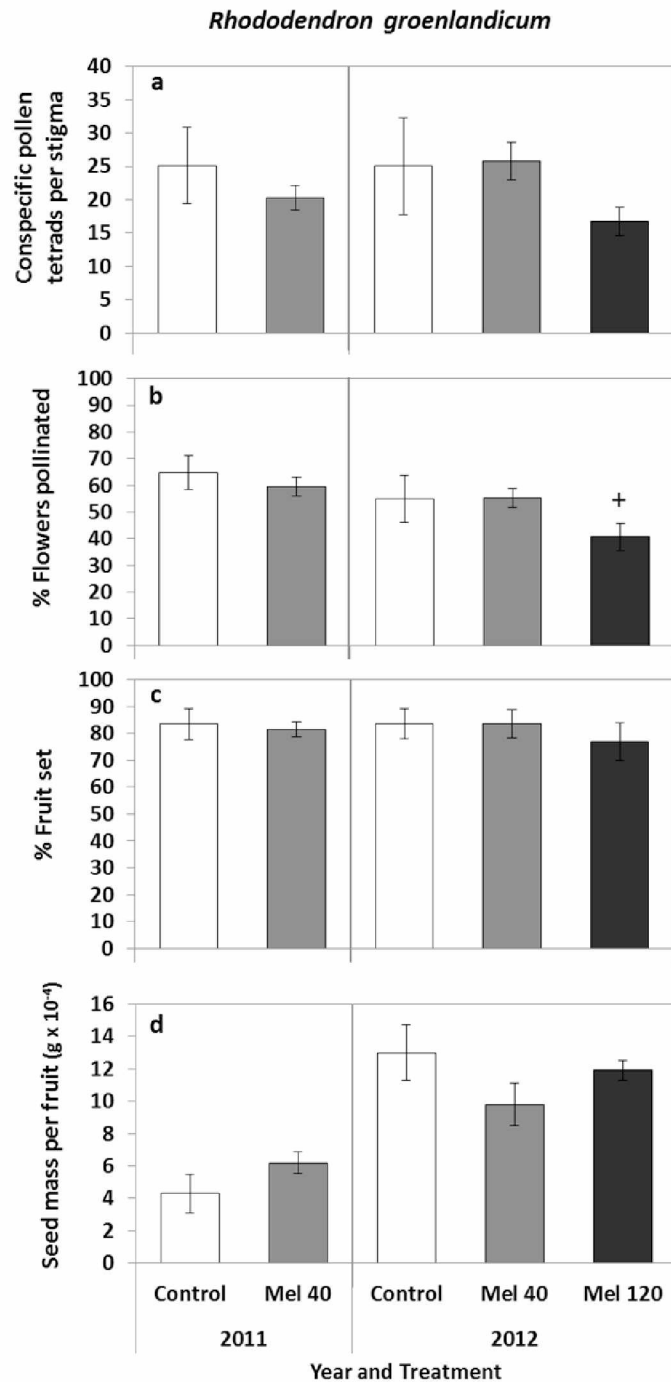


Figure 2.4 *Rhododendron groenlandicum* conspecific pollen loads on stigmas (A), percent flowers pollinated (B), percent flowers setting fruit (C), and number of seeds per fruit (D) in sites without *Melilotus albus* (control) and sites with 40 or 120 *M. albus* plants added (Mel 40 and Mel 120) during the summers of 2011 and 2012. Bars are mean \pm s.e. of site-level averages for each treatment in each year.

Appendix 2.1

Effects of *Melilotus albus* on *Vaccinium uliginosum* fruit set and seed production

Introduction

At the onset of the *Melilotus albus* addition experiment presented in Chapter 2, *Vaccinium uliginosum* was included as a focal species. Under the current conditions in interior Alaska, the flowering times of *Melilotus albus* and *Vaccinium uliginosum* overlap for about 6 days, approximately 15% of the total flowering period for *V. uliginosum* (K.V. Spellman, unpublished data). This is substantially less overlap than for *V. vitis-idaea* and *Rhododendron groenlandicum*, the other focal native species in our study (pers. obs.), which can be up to 15 days of overlap in interior Alaska (K.V. Spellman, unpublished data). *V. uliginosum* is of interest still because the overlap is greater in other parts of the state or continent (C.P.H. Mulder, unpublished data) and because under climate change there might be shifts toward greater overlap. Rapid turnover in the flowers, new flower production over the the months of June and July, and early onset of flowering in our years of study made *V. uliginosum* a logistically challenging species to keep in the study and include in the publishable manuscript. The data from the year I did study *V. uliginosum*, however, may be of use to others interested in blueberry pollination.

Methods

The same methods detailed in Chapter 2 were followed with only a few modifications. Fourteen field sites (out of a total of 18 sites used for the study) had *V. uliginosum* present in abundance in the plant community, 4 control sites and 10 sites with 40 sweetclover plants added

(Mel+40). Due to the small number of open *V. uliginosum* flowers at the time of the experiment other than on the plants marked for tracking fruit set, we were not able to collect stigmas from this species. Many *V. uliginosum* flowers had opened on our marked plants before we began our experiment. As a result, the response variables for this species include the percent flowers setting fruit and seeds per berry only for flowers that were unopened prior to *M. albus* addition.

Results

There was no difference in *V. uliginosum* fruit set or seeds per berry between the sites with 40 *M. albus* and the control sites (fruit set- $F_{(1,12)} = 0.27, p = 0.61$; seeds per berry- $F_{(1,12)} = 0.33, p = 0.58$; Figure 2.5). None of the environmental covariates we measured were supported by our multiple regression analysis to explain *V. uliginosum* fruit set or seed production (Table 2.7).

Conclusion

We did not detect any influence of *M. albus* addition or number of sweetclover inflorescences on *V. uliginosum* fruit set or seed production. In addition to the limited overlap in flowering times for *V. uliginosum* and *M. albus*, these data may support the idea that sweetclover has little competition for pollinator with *V. uliginosum* in interior Alaska. However, with fewer sites and fewer plants available for data collection relative to the other species we sampled in Chapter 2, a lack of statistical power may contribute to these results. The inability for any of our environmental covariates to explain any variation in our response variables further suggests a lack of power. Further research that considers the methodological challenges we faced in our study will be necessary to assess the impact of *M. albus* or earlier flowering invasive plants on *V. uliginosum* reproduction.

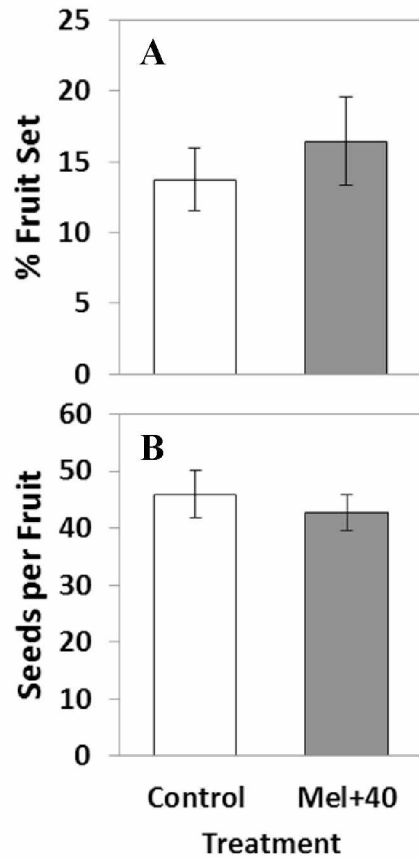


Figure A2.1.1 *Vaccinium uliginosum* percent flowers setting fruit (A), and number of seeds per fruit (B) in sites without *Melilotus albus* (control) and sites with 40 *M. albus* plants added (Mel+40) during the summers of 2011 and 2012. Bars are mean \pm s.e. of site-level averages for each treatment in each year.

Table A2.1.1 Modeled Akaike's Information Criterion average parameter estimates (\bar{b}) and relative variable importance (cumulative parameter weights; $\sum \omega_i$) for candidate variables explaining differences % *V. uliginosum* flowers setting fruit, and seeds per fruit across all sites. Bold values indicate well-supported variables ($\sum \omega_i > 0.55$) and average parameter values for these variables were taken over models with a difference in AICc < 2.

Explanatory Variables	Response Variables			
	% fruit set		total seeds	
	\bar{b}	$\sum \omega_i$	\bar{b}	$\sum \omega_i$
# <i>M. albus</i> inflorescences	.	0.07	-0.005	0.17
canopy cover (%)	0.43	0.17	0.15	0.30
# <i>V. uliginosum</i> flowers	2.48	0.18	-0.73	0.21
# all flowers	0.15	0.15	-0.01	0.11
flower richness	.	0.02	-2.12	0.16
avg. temperature	9.03	0.10	-0.61	0.16
hours of rain	.	0.03	-0.02	0.19

CHAPTER 3

Effects of invasive plant patch size and distance on the pollination and reproduction of native boreal plants¹

¹Spellman KV, Mulder CPH, Carlson ML. Effects of invasive plant patch size and distance on the pollination and reproduction of native boreal plants. Manuscript prepared for submission to the journal *Oecologia*.

Abstract

In pollinator-limited ecosystems in the earliest stages of the invasion process, the effects of invasive plants on the pollination and reproduction of co-flowering native plants may be particularly sensitive to the distance between native and non-native plants. Our study experimentally tests how the distance from invasive plant patches affects the pollination and reproduction of two native boreal plants. We added 0, 40, or 120 flowering *Melilotus albus* individuals to the center of sites with flowering *Vaccinium vitis-idaea* and *Rhododendron groenlandicum* located at five different distances from the center: 1 to 2 m, 3 to 5 m, 8 to 10 m, 15 to 20 m, and 25 to 40 m away. The distance from the invasive plant patch affected the relationship between *M. albus* and the reproductive success of *R. groenlandicum*, but not of *V. vitis-idaea*. Compared to the same distances from the site center in control sites, the percentage of *R. groenlandicum* flowers pollinated and the seed mass per fruit increased close to the *M. albus* patches (1 - 5 m) and decreased at greater distances (8 – 40 m). *M. albus* patch size did not affect the relationship between distance from the invasive plant patch and the pollination and seed production of the native plants. These data suggest that small patches of a rewarding invasive plant increases the spatial variation in pollination and reproduction of some native boreal plants within a site.

Keywords

Boreal forest, invasive species, *Ledum palustre* ssp. *groenlandicum*, *Melilotus albus*, pollination, *Rhododendron groenlandicum*, seed set, spatial scale, *Vaccinium vitis-idaea*

Introduction

Invasive plants are well understood to often alter native plant communities through direct competition with native plants for light, water, and nutrients (reviewed in Levine et al. 2003; Skurski et al. 2014). Indirect competition for pollinator services can also occur with invasive plants that have highly rewarding inflorescences (Chittka and Schürkens 2001). Because many pollinating insects fly substantial distances to obtain floral resources (Osborne et al. 1999; Beekman and Ratnieks 2000; Gathmann and Tschardt 2002; Knight et al. 2005), the scale at which entomophilous invasive plants can affect the reproductive success of native plants is much greater than the effects of direct competition. Some studies have reported net negative effects of invasive plants on the pollination of native plants by decreasing visitation rates to native plants (Waser 1983; Campbell 1985; Brown et al. 2002; Kandori et al. 2009) or increasing the amount of incompatible pollen delivered to the native flowers (Morales and Traveset 2008).

Other studies report overall positive effects through a “pollinator magnet” effect or by increasing pollinator carrying capacity of a site (Moragues and Traveset 2005; Lopezaraiza-Mikel et al. 2007; Tepedino et al. 2008), or no effects (Bartomeus et al. 2008). Most field studies investigating the impact of invasive plants on pollination of native plants occur in relatively small scale plots or transects with the invasive plants dispersed throughout (Lopezaraiza-Mikel et al. 2007; Bartomeus et al. 2008; Muñoz and Cavieres 2008; Bartomeus et al. 2010; Flanagan et al. 2010; Da Silva et al. 2012; plot/transect size in these studies range from 18 m² to 200 m²).

Some authors acknowledge that the scale of their investigation may alter the overall direction of the interactions between invasive plants, pollinators, and native plant species (Lopezaraiza-Mikel et al. 2007; Jakobsson et al. 2009). For example, Lopezaraiza-Mikel et al. (2007) found facilitative effects of invasive *Impatiens glandulifera* on pollinator visitation to native plants. They speculated, however, that competition could be occurring at larger scales if

highly mobile insects like *Bombus* spp. or *Apis mellifera* are being drawn to the invasive plant patch, leaving plants further away, outside their experimental plots, in a deficit for pollinator services. In another example, Jakobsson et al. (2009) compared pollinator visitation rates to native plants in three treatments: 1) large scale areas infested with invasive plants, 2) large scale areas infested with invasive plants with small scale plots where the invasive plant was removed, and 3) large scale uninvaded areas. They found that pollinator visits to native plants in the small scale removal plots were greater than in large scale invaded sites or in uninvaded sites. These studies suggest that the native plants may be experiencing diverse, and perhaps contrasting, reproductive outcomes depending on their proximity to the invasive plant patch.

Only a few studies have considered the role distance from invasive plant patch plays in reproductive interactions between invasive and native plants (Moragues and Travaset 2005; Nielsen et al. 2008; Takakura et al. 2011; Cawoy et al. 2012). The native plant species in these studies typically had highest visitation rates or non-native pollen deposition levels immediately adjacent to the invasive plant patch (Moragues and Travaset 2005; Nielsen et al. 2008; Takakura et al. 2011, Cawoy et al. 2012). Distance from the invasive patch had no effect (Moragues and Travaset 2005, Nielsen et al. 2008, Cawoy et al. 2012) or an inconsistent effect (Takakura et al. 2011) on the seed set of the native plants in these studies.

In boreal forest ecosystems, the distance between an insect-pollinated plant and a patch of abundant invasive flowers may be particularly important in determining the reproductive consequences. Boreal forest ecosystems tend to have fewer flowering species, smaller pollinator pools, and shorter flowering periods than most other ecosystems (Kevan et al. 1993). Thus competition for pollinator service is expected to be particularly high. Second, most non-native species that have established in boreal forest ecosystems occur in relatively small patches where they have spread off the human disturbance footprint (Rose and Hermanutz 2004; Bella 2011;

Sanderson et al. 2012; AKEPIC 2014), so invasive plant impacts are not diffused across broad areas. An invader with large numbers of flowers and high nectar rewards could draw pollinators from substantial distances, leaving plants far from the patch in a deficit for pollinator services during a short boreal flowering season.

Melilotus albus Medik. (*M. albus*, sweetclover), is a highly rewarding invasive plant, which has established along much of the anthropogenic footprint in Alaska and has incipient populations within intact boreal forests. *M. albus* is native to Eurasia and was introduced to Alaska in 1913 as a potential cold-hardy forage and nitrogen-fixing crop (Irwin 1945, Klebesadel 1992), and now occurs throughout Alaska from as far south as Metlakatla (55.122 °N, - 131.561 °W) to north of Coldfoot (67.286 °N, -150.171 °W) at the base of the Brooks Mountain Range (AKEPIC 2014). Aside from several roadsides and a few glacial river floodplains where large continuous patches have established (Conn et al. 2008; Spellman and Wurtz 2011), it occurs only in small discreet patches within intact boreal forest sites (Villano and Mulder 2008; AKEPIC 2014; Spellman et al. 2014). Particularly in comparison to native boreal insect-pollinated plants, *M. albus* offers considerable nectar and pollen resources to floral visitors (Peterson 1989, Malacalza et al. 2005, Tepedino et al. 2008) with an extremely high number of flowers per plant (up to 350,000 flowers per plant; Royer and Dickinson 1999).

In 2011 and 2012, we added *M. albus* patches of two different sizes to sites with native *Vaccinium vitis-idaea* L. (lingonberry or lowbush cranberry) and *Rhododendron groenlandicum* (Oeder) Kron & Judd (formerly *Ledum palustre* ssp. *groenlandicum*; Labrador tea) dominant in the understory, and compared them to control sites with no *M. albus*. Both native boreal species overlap in flowering periods and share pollinators with *M. albus* (Chapter 2). *V. vitis-idaea* and *R. groenlandicum* are self-compatible (Jacquemart and Thompson 1996; Jacquemart 1997; Wheelwright et al. 2006). Both species, however, have decreased fruit and seed set when insect

pollinators are excluded and increase fruit set and seed production when they are supplemented with outcross pollen (Hall and Beil 1970; Fröborg 1996; Jacquemart and Thompson 1996; Davis 2002; Wheelwright et al. 2006).

We previously reported on the mean differences in pollination and subsequent reproduction between sites with and without *M. albus* additions at a coarse scale (Chapter 2). We found that at the site level, pollinator activity and diversity increased when *M. albus* was added to sites. The number of *V. vitis-idaea* seeds per fruit increased when we added a large number (120) of *M. albus* plants compared to sites with a low number (40) of *M. albus* added and control sites. *R. groenlandicum* pollination rates modestly decreased with increasing numbers of *M. albus* flowers. In the present study, we investigate the spatial pattern of these effects within our sites and ask two questions: 1) does the distance from the invasive plant patch affect pollination and seed production of *V. vitis-idaea* and *R. groenlandicum*? and 2) does the relationship between distance from the invasive plant patch and native plant pollination and reproductive success vary with different *M. albus* patch sizes?

Methods

Study area

Sites were located within the Bonanza Creek Boreal Long Term Ecological Research Program (BNZ LTER) research areas near Fairbanks, Alaska (Bonanza Creek Experimental Forest, 64.709 °N, -148.326 °W, and Caribou and Poker Creeks Research Watershed, 65.141 °N, -147.457 °W). Sites were selected to contain abundant flowering *V. vitis-idaea* and *R. groenlandicum* in the understory. Dominant tree species at the sites included *Betula neoalaskana* Sarg., *Populus tremuloides* Michx., *Picea glauca* (Moench) Voss, and *Picea mariana* Mill. Other insect-pollinated native species flowering at the sites at the time of the experiment included *Cornus canadensis* L., *Geocaulon lividum* (Richardson) Fernald,

Moehringia lateriflora (L.) Fenzl, *Rosa acicularis* Lindl., *Rubus chamaemorus* L., *Salix* spp. L., *Vaccinium uliginosum* L., and *Viburnum edule* (Michx.) Raf. *M. albus* did not occur at any of these sites. Compared to the 30-year average precipitation and temperature for June (3.6 cm, 15.4 °C), in 2011 precipitation was higher and temperatures were close to average (4.5 cm, 15.8 °C), and in 2012 precipitation was close to average but temperatures were substantially higher (3.5 cm, 16.4 °C; Alaska Climate Research Center 2014). During the flowering period of *V. vitis-idaea* and *R. groenlandicum* at our sites we measured 173 hours of rain and a mean temperature of 13.6 °C in 2011 and 97 hours of rain and a mean temperature of 15.0 °C in 2012.

Experimental design

In 2011, we selected 17 sites spaced >300 m apart to minimize pollinator movement between sites. Sites were circular and extended 40 m in all directions from the site center (Figure 1). Within each site, 25 circular plots were established for each of the occurring focal species (1 m² plots for *V. vitis-idaea*, and 1.77 m² plots for *R. groenlandicum*). Five plots for each focal species present at the site were placed within five distance ranges from the site center: 1 to 2 m, 3 to 5 m, 8 to 10 m, 15 to 20 m, and 25 to 40 m (Fig. 3.1). Within these plots, five *V. vitis-idaea* or five *R. groenlandicum* stems were marked for tracking fruit and seed production.

Eleven sites were randomly assigned to have 40 flowering *M. albus* plants that were grown in a greenhouse added to the site center (designated “Mel40”), and six were control sites (no *M. albus* added). The sites contained one or both of the focal native species, with 16 sites containing *V. vitis-idaea* (6 control and 10 Mel40) and 15 sites containing *R. groenlandicum* (4 control and 11 Mel40).

In 2012, we discontinued the site that did not have *V. vitis-idaea* and added two new sites to bring the total number of sites to 18. To address the influence of invasive plant patch size on the reproductive success of our focal species, we added a higher *M. albus* addition level to our

design in 2012 (120 plants added, designated “Mel120”). The eighteen sites were allocated to each of the three treatment levels: control, Mel40, and Mel120 (6 sites each). To compare years directly, we retained the same treatments in six of the sites (3 control and 3 Mel40 sites). The remaining three control sites, three Mel40 sites and six Mel120 sites were randomly assigned. In 2012, 18 sites contained *V. vitis-idaea* (6 control, 6 Mel40, and 6 Mel120) and 14 sites contained *R. groenlandicum* (4 control, 6 Mel40, and 4 Mel120).

M. albus was added to the Mel40 or Mel120 sites at the time that *V. vitis-idaea* and *R. groenlandicum* flower buds emerged, but had not yet opened. *M. albus* were grown in the greenhouse in “conetainer” pots (7 cm diameter at the top, 22 cm in length); each pot contained one individual with 5 to 181 inflorescences (mean of 49 ± 18 flowers per inflorescence). Either 40 or 120 pots were placed in the center of the site in holes of similar dimensions so that the top of the pot was flush with the ground surface. *M. albus* density was 15 plants per m^2 , resulting in patch sizes of approximately 2.6 m^2 and 8 m^2 . The number of inflorescences added to each site ranged from 334 to 942 (16,366 to 46,158 total flowers) for Mel40 sites and 1068 to 1608 (52,332 to 78,792 total flowers) for Mel120 sites. The addition levels we used (Mel40 and Mel120) were comparable to the patch sizes found within burned boreal forest in interior Alaska, which are typically in the earliest of invasion stages where they occur (Villano and Mulder 2008). Once flowers of focal native species had dropped their petals (18-28 days after *M. albus* addition), *M. albus* was removed from the sites. To prevent accidental introductions, we removed any immature seeds that appeared on the *M. albus* plants throughout the duration of the experiment. Sites were also visited a year following the experiments to confirm that no *M. albus* plants were present.

Pollination

We collected *V. vitis-idaea* and *R. groenlandicum* stigmas from randomly selected open flowers near each of our marked focal plants. We did not take stigmas from marked plants to avoid interfering with fruit set. Three (in 2011) or five (in 2012) *V. vitis-idaea* and five *R. groenlandicum* stigmas were collected from each of the 25 plots in each site approximately 14 days after the *M. albus* was added. The stigmas were mounted on microscope slides and stained with a basic fuchsin gel (Kearns and Inouye 1993). Each tetrad (in the case of *R. groenlandicum* and *V. vitis-idaea* pollen) or pollen grain (all other species) on the stigma was identified to genus (using anthers collected from all flowering species at the sites for reference) and counted under a compound light microscope. We calculated the percent of well-pollinated flowers in each plot using these pollen counts. Flowers were considered to be “well-pollinated” when they had ≥ 10 conspecific pollen tetrads on the stigma. We selected this threshold because fruit production increases sharply at this pollen level for both focal species in control plots (data not shown). Few stigmas had zero pollen grains on them, making presence or absence of pollen inadequate to detect variation in proportion of flowers that were pollinated.

Proportion of heterospecific pollen grains on the stigmas was low across all sites (3.2 ± 0.3 % for *V. vitis-idaea* and 0.8 ± 0.2 % for *R. groenlandicum*). In sites where *M. albus* was added, the mean percent *M. albus* pollen of total pollen grains on a stigma was also very low (0.4 ± 0.1 % for *V. vitis-idaea* and 0.1 ± 0.03 % for *R. groenlandicum*, typically one or two grains where it occurred). We recorded the range of distances where we detected *M. albus* pollen on focal stigmas to provide a sense of the potential scale at which *M. albus* could influence pollinator behavior within our sites.

Seed production

To determine seed production per fruit in *V. vitis-idaea* we dissected up to 5 berries per marked plant and counted the number of seeds produced under a dissecting microscope. For *R. groenlandicum*, which has minute seeds that are released as the fruit ages and dries, we dried inflorescences at 65 °C until the fruits opened and released the seeds. The weight of the seeds was divided by the number of fruits on the inflorescences to derive seed mass per fruit.

Native vegetation characteristics

We could not randomly select the location of the center of the site because of the requirement for at least 25 flowering individuals 1-2 m from the center. Therefore, site centers had to be placed within a relatively dense patch of *V. vitis-idaea* and *R. groenlandicum*. To detect if this logistical constraint may have affected other vegetation characteristics within our different distance categories or driven any of our results, we measured biotic variables at each plot that we expected to influence our response variables. Tree canopy cover was estimated for each of the 25 plots using a convex spherical crown densiometer (Model A; Forest Densiometers, Bartlesville, Oklahoma, USA) on the north and south edges of the plot. To provide an estimate of flower abundance and richness, we counted the number of open heterospecific and conspecific flowers and flower buds present for each insect-pollinated species within each of the 25 plots per site at the time of *M. albus* addition.

Analysis

We performed the statistical analyses using SAS v.9.1 (SAS Institute, Cary, North Carolina). We used percent flowers receiving ≥ 10 pollen tetrads (“% pollinated flowers”) and number of seeds per fruit for *V. vitis-idaea* or seed mass per fruit for *R. groenlandicum* (“seeds per fruit”) as our response variables. Mean *R. groenlandicum* seed mass per fruit for each plot was square root transformed to meet the assumptions of normality and constant variance. We

isolated the response of our focal plants in relationship to distance from the site center within our sites by calculating the residuals of our response variables in each five distance categories within our sites (1- 2 m, 3 - 5 m, 8 - 10 m, 15 - 20 m, and 25 - 40 m) relative to the site mean. We used measured values in our previously reported study on the site-level effects of *M. albus* addition, and use residuals here to eliminate the high variation among sites and isolate the within-site effects. Due to large differences in our response variables in the two years of our study at the between-site scale, we performed the analysis separately for each year. Using mean residuals for each distance category from each site, we conducted ANCOVA to determine if the relationships between distance and our response variables differed between treatment levels when we treated distance as a continuous variable (the ln-transformed mean value of each distance category).

Because of the possibility of a non-linear relationship, we also conducted MANOVA using only the residuals from the first four distance categories in each site to test if treatment could explain the variation in responses across the distance categories. We omit one distance category to avoid violating the assumption of independence, because the sum of all five residuals is equal to zero. We use the MANOVA approach rather than individual ANOVAs at testing for a treatment effect each distance category to reduce the risk of committing type I error. We tested for a relationship between distance from site center and native vegetation characteristics within our sites using correlation analysis. Due to high variation among sites, we used the residuals of these native vegetation variables in each distance category relative to the site-level mean for the analysis.

Results

Distance range of M. albus pollen deposition

In sites where it was added, *M. albus* pollen was detected on both *V. vitis-idaea* and *R. groenlandicum* stigmas from the edge of the invasive plant patch to the outermost plots in our

sites (40 m from the site center; Table 3.1).

***M. albus* effect and distance**

V. vitis-idaea- We found little evidence that *M. albus* addition altered the relationship between distance from the site center and *V. vitis-idaea* percent flowers pollinated or seeds per berry in either year of our study (Fig. 3.2, Fig. 3.3). Similarly, we did not detect any significant effect of *M. albus* treatment level in our MANOVA analysis for 2011 or 2012 (Table 3.2).

R. groenlandicum- Control sites showed greater increases in seed mass per fruit with distance from the site center than the Mel40 sites in 2011 (Fig. 3.4; $\ln(\text{distance}) \times \text{treatment}$ interaction $F_{(1,69)} = 4.37$, $p = 0.04$). In 2012, the residuals for percent *R. groenlandicum* flowers pollinated had a significant positive relationship with distance from the site center in control sites ($p = 0.03$) but not in Mel40 or Mel120 sites (Fig. 3.4). The same pattern occurred for seed mass per fruit in 2012 (Fig. 3.4), but the positive relationship between distance from site center and the residuals of seed mass per fruit was only marginally significant in the control sites ($p = 0.06$). When we treated distance as a categorical variable, we observed similar trends (though non-significant in our MANOVA analysis; Table 3.2). The percentage of *R. groenlandicum* flowers pollinated in the 25 - 40 m distance category tended to be higher in control sites than in sites with *M. albus* added for both years (Fig. 3.5a,c) and the seed mass per fruit 1 - 2 m from the site center tended to be lower in control sites than in *M. albus* addition sites (Fig. 3.5b,d).

Native vegetation and distance

Both the total number of all flowers and the number of *R. groenlandicum* flowers in plots increased with increasing distance from the site center within our sites (correlations between $\ln(\text{distance})$ and residuals: all flowers- Pearson's $r = 0.31$, $p = 0.002$; *R. groenlandicum* flowers- $r = 0.30$, $p = 0.009$). The distance from the site center was not correlated with tree canopy cover ($r = -0.05$, $p = 0.59$), flower richness ($r = 0.15$, $p = 0.15$), and number of *V. vitis-idaea* flowers (r

= 0.20, $p = 0.06$) within the sites. *V. vitis-idaea* flowers comprised $36 \pm 6 \%$ and *R. groenlandicum* flowers comprised $75 \pm 2 \%$ of the total number of flowers in the plots in sites where they occurred.

Discussion

Many field studies on the effects of invasive plants on pollination and reproduction of native plants use small scale plots where invasive plants are dispersed throughout (Lopezaraiza-Mikel et al. 2007; Bartomeus et al. 2008; Muñoz and Cavieres 2008; Bartomeus et al. 2010; Flanagan et al. 2010; Da Silva et al. 2013). There are many cases, particularly in very recently invaded sites, where applying results from these studies may lead to misleading inferences about the reproductive consequences to native plants. For example, species-poor plant communities with few pollinators, as is generally the case in the boreal forest, are expected to be vulnerable to even small patches of an abundantly flowering invasive plant like *M. albus* (cf. Carlson et al. 2008). We detected *M. albus* pollen on both *V. vitis-idaea* and *R. groenlandicum* stigmas up to 40 meters from the center of the invasive plant patch, the furthest distances we sampled. This finding suggests that small patches of an entomophilous invasive plant can affect the pollinators of native co-flowering boreal species at larger spatial scales than anticipated based on the existing body of literature.

The distance from the invasive plant patch affected the relationship between *M. albus* and the pollination and reproductive success of *R. groenlandicum*, but not of *V. vitis-idaea*. This finding is consistent with Moragues and Travaset (2005) who found that distance from invasive *Carpobrotus* had a different effect on the pollination of two different native plant species. In the instances where they detected invasive plant pollen on native *Cistus salviifolius* stigmas, it was only for plants less than 10 m away from invasive plant patch, while invasive plant pollen was only found on *Lotus cytisoides* stigmas greater than 30 m away. Similarly, Cawoy et al. (2012)

saw greater increases in bumblebee visitation rates with increasing proximity to the *Impatiens glandulifera* patch for *Chamerion angustifolium* than for *Aconitum napellus* (Cawoy et al. 2012).

As a result of our site design, the number of *R. groenlandicum* flowers per plot increased at greater distances from the site center within our sites. There was not a strong relationship between distance and the abundance of *V. vitis-idaea* flowers. This trend helps to explain the positive relationship between distance and the *R. groenlandicum* pollination and seed production in the control sites. Fewer *R. groenlandicum* flowers in the plots near the center of the site likely decreased attractiveness of the plot for visiting pollinators (cf. Bosch and Waser 2001) and increases the probability of self-pollination, which reduces seed set in *R. groenlandicum* (Wheelwright et al. 2006). The addition of *M. albus* appears to compensate for the lower number of *R. groenlandicum* flowers at the site center and reduce the effect of distance on seed production. This result suggests that the relative orientation of an invasion front and spatial patterns of the native plants can have important consequences for the impact an invasive plant has on pollination and reproduction.

The degree of shared pollinators between the *M. albus* and the native flowers also helps explain why we saw a difference in the role of distance in invasive-native reproductive interactions between our two focal species. A concurrent study at our sites found that *R. groenlandicum* shared a greater number of visiting pollinators with *M. albus* than *V. vitis-idaea* (L. Schneller, unpublished data). In 2012, *M. albus* tended to increase the percentage of flowers that were well-pollinated close to the site center relative to the control sites, suggesting *M. albus* is attracting pollinators to the center of the site. If this is the case, *R. groenlandicum* flowers close to the invasive plant patch may benefit from the increased availability of compatible pollinators. This explanation is consistent with the findings of Nielsen et al. (2008), who found

increased visitation rates to a native plant species directly adjacent to an invasive plant patch, but not at further distances, and attributed the result to a “magnet effect” on shared pollinators. Similarly, a bumblebee species was noted to forage indiscriminately between the native *C. angustifolium* and adjacent invasive *I. glandulifera*, which increased visitation rates at 0 m, but not 15 m from the invasive plant patch (Cawoy et al. 2012).

At the site scale, the abundance of *M. albus* added to the site was important to determining the overall impact of the invasive on the pollination and reproduction of both our focal species (Chapter 2). Our present study shows that the spatial pattern of these effects within the sites, however, did not vary with the invasive plant abundance level. This departs from the previous studies that have found important interactions between the invasive plant abundance and distance from nearest invasive plant in explaining the reproductive consequences for native plants (Takakura et al. 2011, Cawoy et al. 2012). However, by using residuals for our analysis, we were able to isolate distance effects within our sites, then ask if the pattern was different when different abundances of invasive plant were added, which these studies did not do. It is also possible that the spatial distribution of reproductive interactions between *M. albus* and the native focal species would have differed had we used even greater abundances of *M. albus*, similar to the abundances in invaded sites along roadsides and rivers. Further, we do not know what happens to pollination and seed production of the native focal species beyond 40 m from *M. albus*, which may have differed between our two *M. albus* abundance levels. Further research is needed to address the impacts of invasive plants in the boreal forest at larger spatial scales and at higher abundances.

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References

- AKEPIC -Alaska Exotic Plant Information Clearing House (2014) AKEPIC Mapping Project Inventory Field Data. University of Alaska Anchorage Alaska Natural Heritage Program and USDA Forest Service, Anchorage, Alaska. Retrieved 9 September 2014 from <http://akweeds.uaa.alaska.edu/>
- Alaska Climate Research Center (2014) Monthly city summary archive. University of Alaska Fairbanks Geophysical Institute, Fairbanks, Alaska. Retrieved 11 December 2014 from <http://climate.gi.alaska.edu/city-archive/>
- Bartomeus I, Bosch J, Vila M (2008) High invasive pollen transfer, yet low deposition on native stigmas in a *Carpobrotus*-invaded community. *Annals of Botany* 102: 417–424
- Bartomeus I, Vila M, Steffan-Dewenter I (2010) Combined effects of *Impatiens glandulifera* invasion and landscape structure on native plant pollination. *Journal of Ecology* 98: 440–450
- Beekman M, Ratnieks FLW (2000) Long-range foraging by the honey-bee, *Apis mellifera* L. *Functional Ecology* 14: 490–496
- Bella EM (2011) Invasion prediction on Alaska trails: distribution, habitat, and trail use. *Invasive Plant Science and Management* 4:296–305.
- Bosch, M., and N. M. Waser. 2001. Experimental manipulation of plant density and its effect on pollination and reproduction of two confamilial montane herbs. *Oecologia* 126:76-83.
- Brown BJ, Mitchell RJ, Graham SA (2002) Competition for pollination between an invasive species (purple loosestrife) and a native congener. *Ecology* 83:2328–2336
- Campbell DR (1985) Pollinator sharing and seed set of *Stellaria pubera*: competition for pollination. *Ecology* 66:544–563

- Carlson ML, Lapina IV, Shephard M, Conn JS, Densmore R, Spencer P, Heys J, Riley J, Nielsen J (2008) Invasiveness ranking system for non-native plants of Alaska. Technical Paper R10-TP-143, USDA Forest Service, Alaska Region, Anchorage, AK.
- Cawoy V, Jonard M, Mayer C, Jacquemart AL (2012) Do abundance and proximity of the alien *Impatiens glandulifera* affect pollination and reproductive success of two sympatric co-flowering native species? *Journal of Pollination Ecology* 10:130-139
- Chittka L, Schürkens S (2001) Successful invasion of a floral market. *Nature* 411:653
- Conn JS, Beattie KL, Shephard ML, Carlson ML, Lapina I, Hebert M, Gronquist R, Densmore R, Rasy M (2008) Alaska *Melilotus* invasions: distribution, origin, and susceptibility of plant communities. *Arctic, Alpine, and Antarctic Research* 40:298–308
- Da Silva EM, King VM, Russell-Mercier JL, Sargent RD (2013) Evidence for pollen limitation of a native plant in invaded communities. *Oecologia* 172:469–476
- Davis AN (2002) Pollination biology of the lingonberry, *Vaccinium vitis-idaea* subsp. *minus* L. Master's Thesis. University of Alaska Fairbanks, Fairbanks, Alaska.
- Flanagan RJ, Mitchell RJ, Karron JD (2010) Increased relative abundance of an invasive competitor for pollination, *Lythrum salicaria*, reduces seed number in *Mimulus ringens*. *Oecologia* 164:445–454
- Fröborg, H. (1996) Pollination and seed production in five boreal species of *Vaccinium* and *Andromeda* (Ericaceae). *Canadian Journal of Botany* 74:1363-1368
- Gathmann A, Tschardt T (2002) Foraging ranges of solitary bees. *Journal of Animal Ecology* 71: 757–764
- Hall IV, Beil CE (1970) Seed germination, pollination, and growth of *Vaccinium vitis-idaea* var. *minus* Lodd. *Canadian Journal of Plant Science* 50:731-732

- Irwin DL (1945) Forty-seven years of experimental work with grasses and legumes in Alaska. College, Alaska: University of Alaska Agricultural Experiment Station Bulletin, 12: 47
- Jacquemart AL (1997) Pollen limitation three sympatric species of *Vaccinium* (Ericaceae) in the Upper Ardennes, Belgium. *Plant Syst Evol* 207:159-172
- Jacquemart AL, Thompson JD (1996) Floral and pollination biology of three sympatric *Vaccinium* (Ericaceae) species in the upper Ardennes, Belgium. *Canadian Journal of Botany* 74:210-221
- Jakobsson A, Padrón B, Traveset A (2009) Competition for pollinators between invasive and native plants: effects of spatial scale of investigation (note). *Ecoscience* 16:138-141
- Kandori I, Hirao T, Matsunaga S, Kurosaki T (2009) An invasive dandelion unilaterally reduces the reproduction of a native congener through competition for pollination. *Oecologia* 159:559–569
- Kevan PG, Tikhmenev EA, Usui M (1993) Insects and plants in the pollination ecology of the boreal zone. *Ecological Research* 8:247–267
- Klebesadel LJ (1992) Morphological, physiological, and winterhardiness comparisons among latitudinal ecotypes of biennial sweetclover (*Melilotus* species) in subarctic Alaska. Bulletin 91 of Agricultural and Forestry Experiment Station, School of Agriculture and Land Resources Management. University of Alaska Fairbanks, Palmer, Alaska
- Knight ME, Martin AP, Bishop S, Osborne JL, Hale RJ, Sanderson A et al. (2005). An interspecific comparison of foraging range and nest density of four bumblebee (*Bombus*) species. *Mol Ecol* 14:1811–1820
- Levine JM, Vilà M, D'Antonio CM, Dukes JS, Grigulis K, Lavorel S (2003) Mechanisms underlying the impacts of exotic plant invasions. *Proc R Soc Biol Sci Ser B* 270:775–781

- Lopezaraiza-Mikel ME, Hayes RB, Whalley MR, Memmott J (2007) The impact of an alien plant on a native plant-pollinator network: an experimental approach. *Ecology Letters* 10:539–550
- Malacalza NH, Caccavari MA, Fagúndez G, Lupano CE (2005) Unifloral honeys of the province of Buenos Aires, Argentina. *J Sci Food Agric* 85:1389–1396
- Moragues E, Traveset A (2005) Effect of *Carpobrotus* spp. on the pollination success of native plant species of the Balearic Islands. *Biol Conserv* 122: 611–619
- Morales CL, Traveset A (2008) Interspecific pollen transfer: magnitude, prevalence and consequences for plant fitness. *Critical Reviews in Plant Sciences* 27:221–238
- Muñoz AA and Cavieres LA (2008) The presence of a showy invasive plant disrupts pollinator service and reproductive output in native alpine species only at high densities. *Journal of Ecology* 96:459–67
- Nielsen C, Heimes C, Kollmann J (2008) Little evidence for negative effects of an invasive alien plant on pollinator services. *Biol Invasions* 10:1353–1363
- Osborne JL, Clark SJ, Morris RJ, Williams IH, Riley JR, Smith AD et al. (1999) A landscape-scale study of bumble bee foraging range and constancy, using harmonic radar. *J Appl Ecol* 36: 519–533
- Peterson SF (1989) Beekeeping under the northern lights. *American Bee Journal* 129:33–35
- Rose M, Hermanutz L (2004) Are boreal ecosystems susceptible to alien plant invasion? Evidence from protected areas. *Oecologia* 139: 467–477
- Royer F, Dickinson R (1999) *Weeds of the Northern U.S. and Canada*. The University of Alberta Press, Edmonton, Alberta
- Sanderson LA, McLaughlin JA, Antunes PM (2012) The last great forest: a review of the status of invasive species in the North American boreal forest. *Forestry* 85: 329–339

- Skurski TC, Rew LJ, Maxwell BD. 2014. Mechanisms underlying nonindigenous plant impacts: a review of recent experimental research. *Invasive Plant Science and Management* 7:432–444.
- Spellman BT, Wurtz T (2011) Invasive white sweetclover (*Melilotus officinalis*) impacts native recruitment along rivers in interior Alaska. *Biological Invasions* 13:1779–1790
- Spellman KV, Mulder CPH, Hollingsworth TN (2014) Susceptibility of burned black spruce (*Picea mariana*) forests to non-native plant invasions in Interior Alaska. *Biological Invasions* 16:1879-1895
- Takakura K, Matsumoto T, Nishida T, Nishida S (2011) Effective range of reproductive interference exerted by an alien dandelion, *Taraxacum officinale*, on a native congener. *Journal of Plant Research* 124:269–276
- Tepedino VJ, Bradley BA, Griswold TL (2008) Might flowers of invasive plants increase native bee carrying capacity? Intimations from Capitol Reef National Park, Utah. *Natural Areas Journal* 28:44–50
- Villano KL, Mulder CPH (2008) Invasive plant spread in burned lands of interior Alaska. Technical report for National Park Service-Alaska Region and National Aeronautics and Space Administration, Fairbanks, Alaska
- Waser NM (1983) Competition for pollination and floral character differences among sympatric plant species: a review of evidence. In: Jones CE, Little RJ (eds) *Handbook of experimental pollination biology*. Van Nostrand Reinhold, New York, pp 277–293
- Wheelwright NT, Dukeshire EE, Fontaine JB, Gutow SH, Moeller DA, Schuetz JG, Smith TM, Rodgers SL, Zink AG (2006) Pollinator limitation, autogamy and minimal inbreeding depression in insect-pollinated plants on a boreal island. *American Midland Naturalist* 155: 19-38

Table 3.1 Range of distances from the site center where *M. albus* pollen was detected on *V. vitis-idaea* and *R. groenlandicum* stigmas for each year and *M. albus* addition level.

Species	Year	Treatment	# stigmas with <i>M. albus</i> pollen / total # stigmas	% stigmas with Mel pollen	Min - max distance (m)
<i>V. vitis-idaea</i>	2011	Mel40	54 / 673	8.0 %	1.2 – 38.5
	2012	Mel40	28 / 594	4.7 %	1.6 – 40.0
		Mel120	31 / 589	5.3 %	1.6 – 37.5
<i>R. groenlandicum</i>	2011	Mel40	67 / 1115	6.0 %	1.3 – 40.0
	2012	Mel40	3 / 621	0.5 %	4.4 – 16.7
		Mel120	9 / 388	2.3 %	11.6 – 32.3

Table 3.2 MANOVA results for models testing for *M. albus* addition treatment effect on the residuals of percent flowers pollinated and number of seeds per fruit (for *V. vitis-idaea*) or square root seed mass (g) per fruit (for *R. groenlandicum*) across the first four distance categories from the site center (1-2 m, 3-5 m, 8-10 m, 15-20 m).

Focal Species	Year	Residuals of percent flowers pollinated					Residuals of seeds (or sqrt seed mass) per fruit				
		Wilks' λ	<i>F</i>	num df	denom df	<i>P</i>	Wilks' λ	<i>F</i>	num df	denom df	<i>p</i>
<i>V. vitis-idaea</i>	2011	0.74	0.69	4	8	0.62	0.54	2.10	4	10	0.16
	2012	0.58	0.93	8	24	0.51	0.52	1.07	8	22	0.42
<i>R. groenlandicum</i>	2011	0.56	1.96	4	10	0.18	0.78	0.56	4	8	0.78
	2012	0.60	0.36	8	10	0.92	0.22	2.00	8	14	0.12

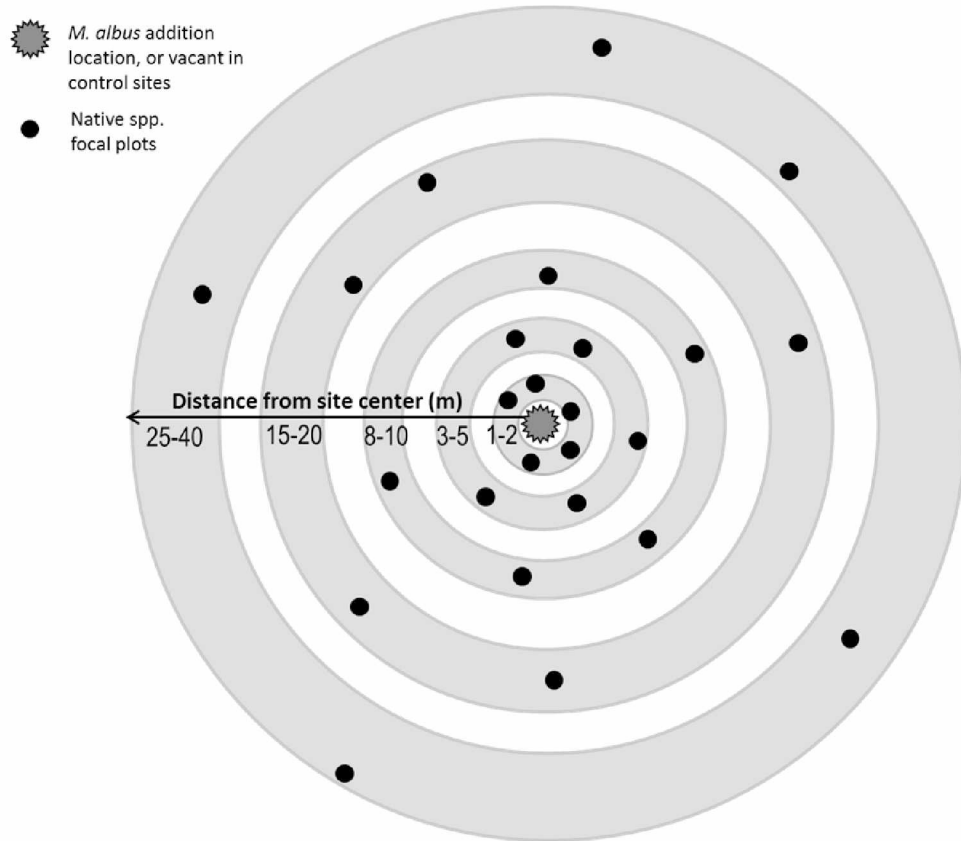


Figure 3.1 Site layout used to investigate the role of distance from invasive plant patch on pollination and sexual reproduction of native ericaceous plants. Native plant focal plots were established at five distance categories from the site center (1-2 m, 3-5 m, 8-10 m, 15-20 m, and 25-40 m). Five sampling and observation plots for *V. vitis-idaea* and/or five plots for *R. groenlandicum* were allocated to each distance category. Control sites had no *M. albus* added, while *M. albus* addition sites had 40 or 120 potted individuals added to the site center.

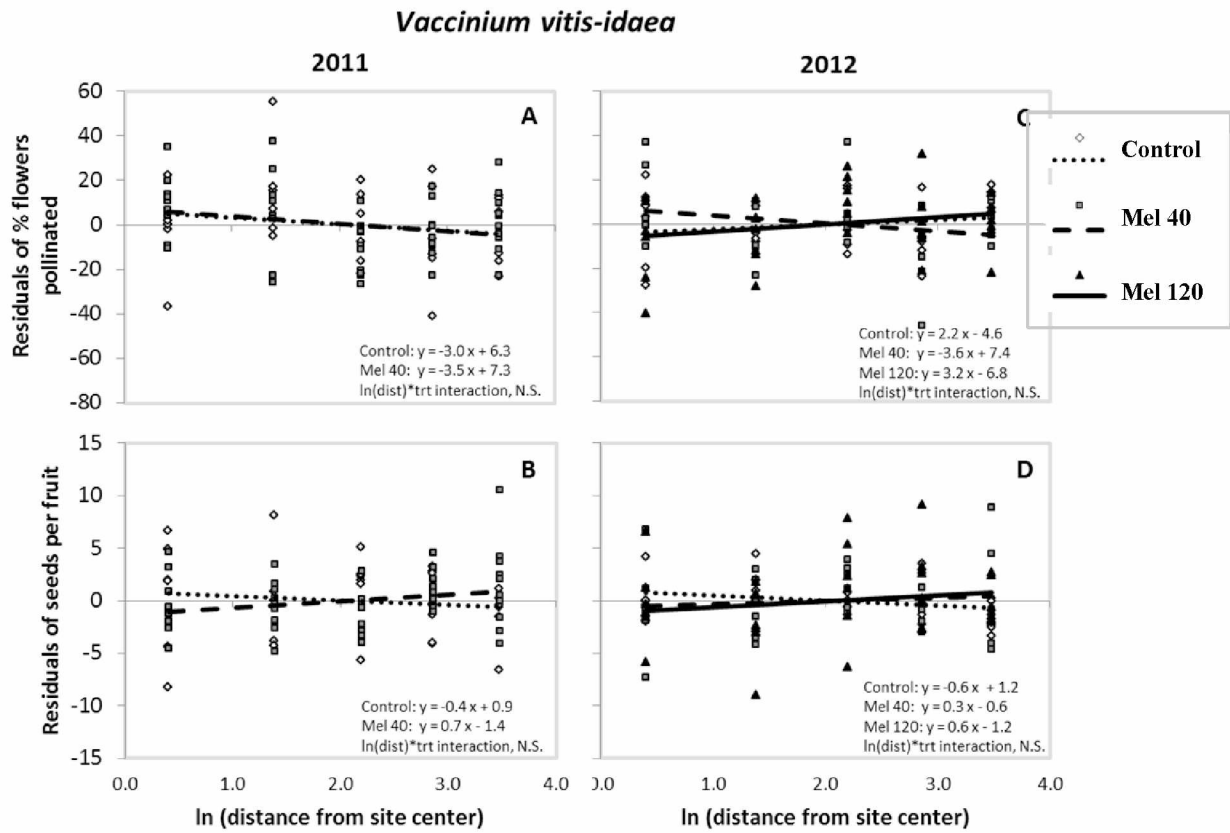


Figure 3.2 Relationship between ln-transformed distance from site center and residuals of *Vaccinium vitis-idaea* percent flowers pollinated (A, C) and seeds per fruit (B, D) in control sites, and sites with 40 *M. albus* or 120 *M. albus* added in 2011 and 2012. Residuals for each distance category in each site were calculated as the difference from the site mean. Regression equations for each treatment and the significance of the ANCOVA ln(distance) by treatment interaction term are shown for each response variable in each year. “N.S.” is “not significant.”

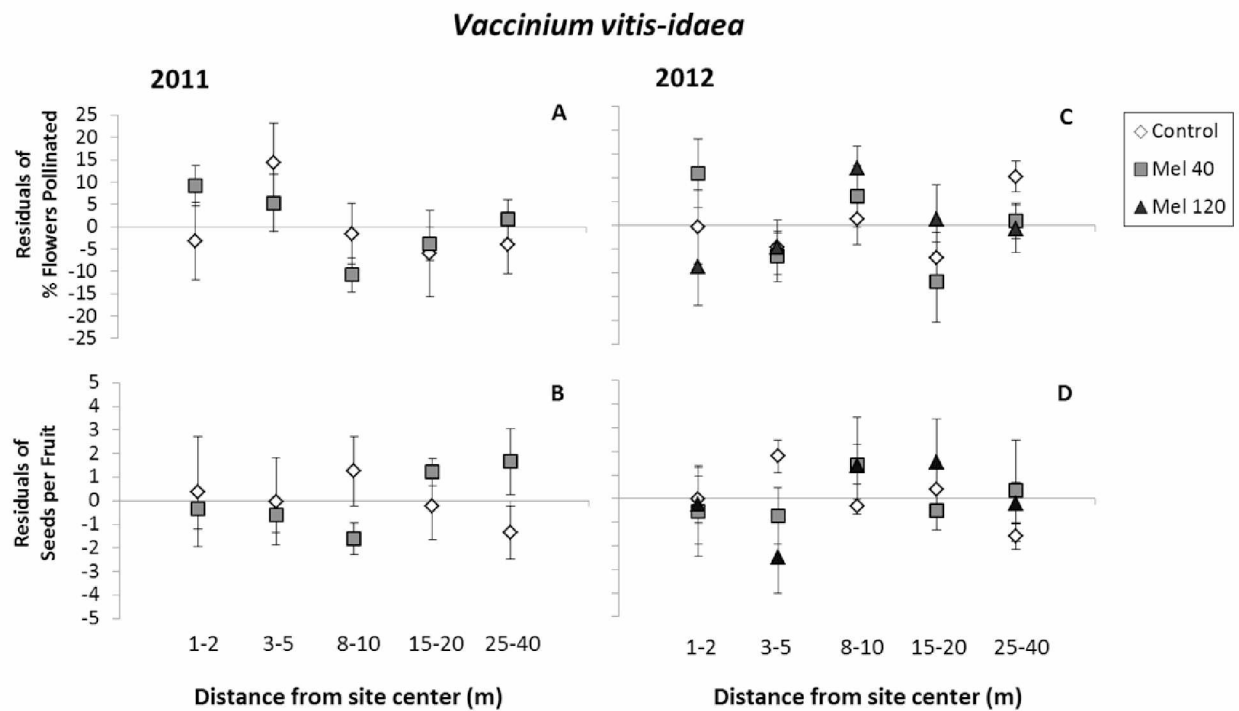


Figure 3.3 Mean (\pm s.e.) residuals of *Vaccinium vitis-idaea* percent flowers pollinated and seeds per fruit for each distance category in control sites, and sites with 40 *M. albus* or 120 *M. albus* added in 2011 and 2012. Residuals for each distance category were calculated as the difference from the site mean and averaged across all sites for the treatment in each year. No significant treatment effects ($p \leq 0.05$) were detected for either variable in either year.

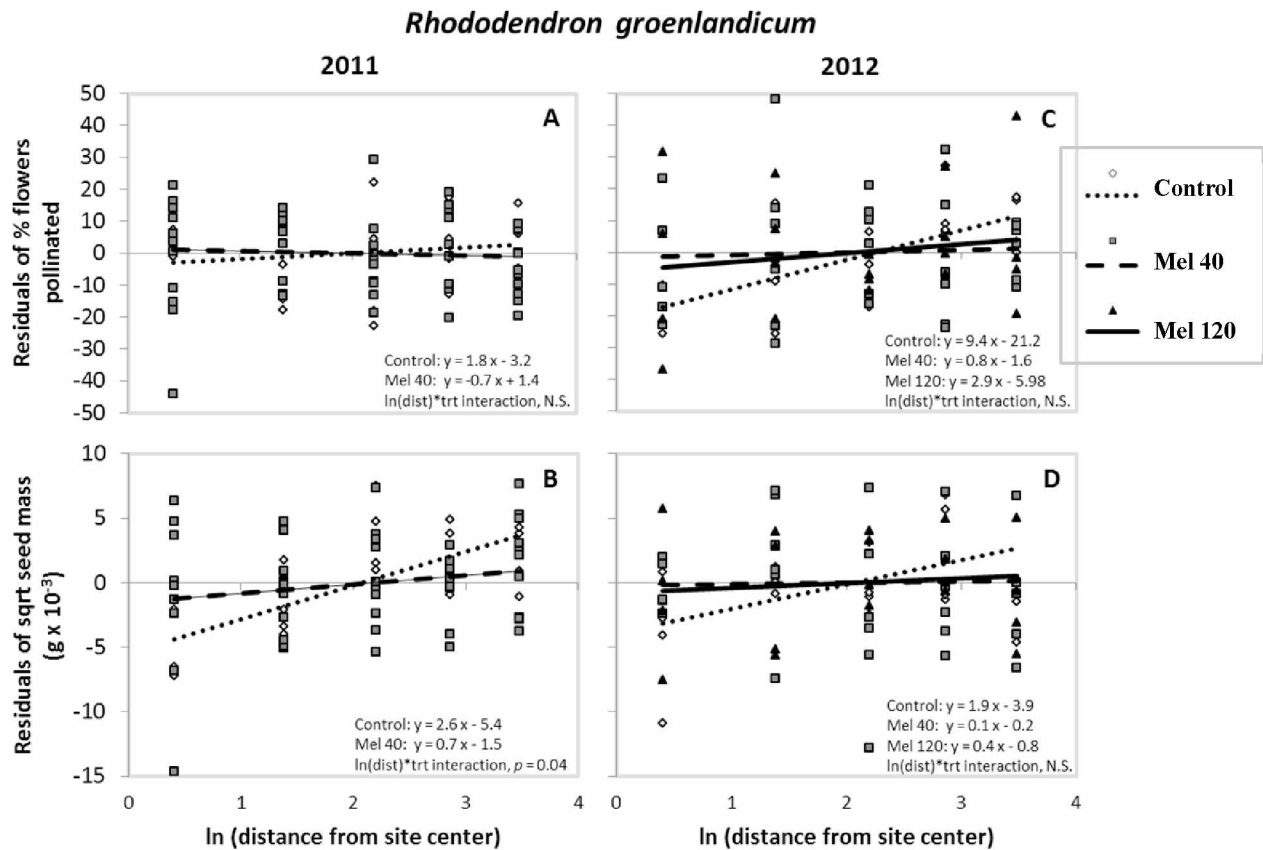


Figure 3.4 Relationship between ln-transformed distance from site center and residuals of *Rhododendron groenlandicum* percent flowers pollinated (A, C) and seeds per fruit (B, D) in control sites, and sites with 40 *M. albus* or 120 *M. albus* added in 2011 and 2012. Residuals for each distance category in each site were calculated as the difference from the site mean. Regression equations for each treatment and the significance of the ANCOVA ln(distance) by treatment interaction term are shown for each response variable in each year. “N.S.” is “not significant.”

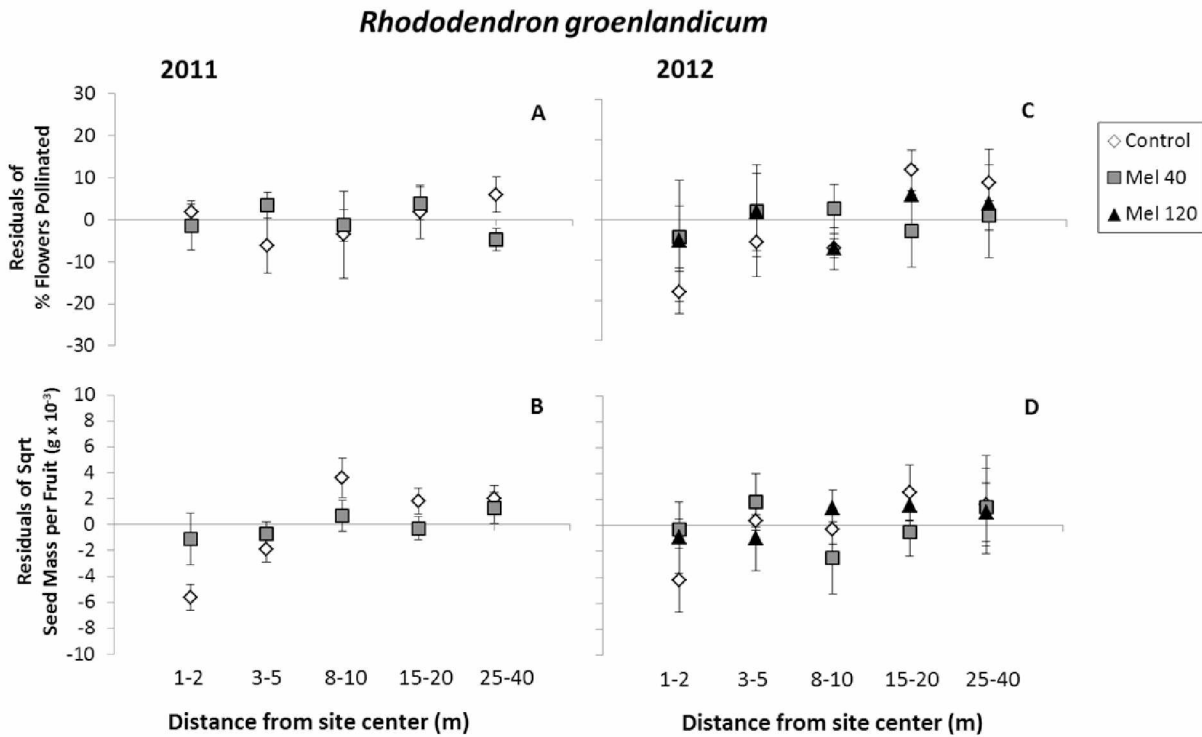


Figure 3.5 Mean (\pm s.e.) residuals of *Rhododendron groenlandicum* percent flowers pollinated and seed mass per fruit ($\text{g} \times 10^{-3}$) for each distance category in control sites, and sites with 40 *M. albus* or 120 *M. albus* added in 2011 and 2012. Residuals for each distance category were calculated as the difference from the site mean and averaged across all sites for the treatment in each year. No significant treatment effects ($p \leq 0.05$) were detected for either variable in either year.

CHAPTER 4

Validating herbarium-based phenology models using citizen science data¹

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Abstract

Both herbarium specimens and citizen science observations have become increasingly popular sources of phenology data for investigating the consequences of a warming climate. We developed and tested a novel technique that uses high quality citizen science observations to provide an independent validation of phenology models derived from herbarium specimens. We demonstrate the technique using flowering phenology of three species that overlap in flowering times and share pollinators: one non-native species (*Melilotus albus*) and two native berry-producing species (*Vaccinium vitis-idaea* and *V. uliginosum*). We used data from across northern North America that spanned 120 years to develop models of historical flowering and fruiting phenology. We validated the models using data collected by citizen scientists at 93 phenology monitoring sites across Alaska from 2012 to 2013. Using this approach we were able to evaluate the strengths and weaknesses of the herbarium dataset. We found that our models were valid for providing an understanding of the relative shifts in phenology of our species across space and time, but needed further calibration to provide accurate predictions for specific dates and locations. Our results support the notion that herbarium data are valid for addressing questions such as testing for shifts in phenology over time. This approach is applicable to other aspects of herbarium data, such as changes in leaf-out, senescence, or first-flowering dates. Further, by actively engaging citizens in the research process, this method can provide social and educational benefits that other model validation techniques cannot provide.

Key Words

Climate change, community-based monitoring, flowering, invasive species, natural history collections, public participation in scientific research

Introduction

A solid understanding of phenology, the timing of biological events, has become increasingly important for advancing our ability to forecast the consequences of global climate change (Penñelas and Filella 2001, Parmesan and Yohe 2003). Plant phenology is particularly sensitive to climate cues (Badeck et al. 2004, Estrella et al. 2007, Forrest and Miller-Rushing 2010) and the direction and magnitude of changes in phenology among different species can have significant consequences for plant reproduction (Hegland et al. 2009, Kudo 2014), community structure (CaraDonna et al. 2014), ecosystem processes (Fridley 2012), trophic interactions (Visser et al. 2012), species distributions (Chaine 2010, Hulme 2011), and biosphere-atmosphere climate feedbacks (Penñelas et al. 2009, Richardson et al. 2013). Researchers have increasingly turned to two sources of data that can span the vast spatial and temporal scales necessary to address these issues: herbarium specimens and citizen science observations.

Over the past decade, herbarium records have become a popular source of historical plant phenology data for global change research (Primack et al. 2004, Miller-Rushing et al. 2006, Lavoie and Lachance 2006, Gallagher et al. 2009, Neil et al. 2010, Robbirt et al. 2011, Calinger et al. 2013, Everill et al. 2014, Hart et al. 2014). Herbarium specimens include dates and collection locations, are found among natural history collections all over the globe, and have been collected over long time scales (more than a century in North America and multiple centuries in Europe, for example). These attributes make them effective tools with which to model plant responses to climate over long time periods, multiple species, and large spatial scales (Miller-Rushing et al. 2006). Despite these benefits, non-random, opportunistic collection efforts are likely to result in biases in herbarium data sets. Strong geographic biases have been demonstrated in biodiversity collections, including herbarium collections, with sample locations

tending to be clustered in easily accessible locations (e.g. near cities or along rivers and roadsides) or in nature reserves (Reddy and Davalos 2003, Kadmon et al. 2003, Sanchez-Fernandez et al. 2008, Schmidt-Lebuhn et al. 2012). Other herbarium collection biases include underrepresentation of plants that are spiny, small, or have green or brown inflorescences (Schmidt-Lebuhn et al. 2013). These biases toward certain growth forms and micro-climates (such as urban or roadside heat bubbles; Kadmon et al. 2003) could skew predictions of phenology derived from herbarium data. Further, collectors may be more inclined to select plants that are in full flower when they are easiest to accurately identify. As a result, models derived from herbarium records could over-estimate the length of time a species is in peak flower (Miller-Rushing et al. 2006).

In light of these biases, several approaches from traditional plant phenological research have been used to validate herbarium-based phenology models. Two common validation techniques include correlational approaches comparing herbarium model predictions with either on-the-ground observations by scientists or satellite imagery of vegetation greening (Primack et al. 2004, Bolmgren and Lunnberg 2005, Miller-Rushing et al. 2006, Robbirt et al. 2011, Park 2012). Field-based observations of phenology have the ability to capture the phenological stages at daily or weekly intervals and cover a large diversity of species. This method of data collection for validation, however, is limited in both spatial and temporal scale, with teams of scientists typically only having the resources to cover a few field sites over a few years (Primack et al. 2004, Miller-Rushing et al. 2006). Satellite imagery, such as MODIS (“Moderate Resolution Imaging Spectroradiometer”) measurement of green-up or senescence, offers a phenology data source where larger scales can be investigated and vast quantities of data can be accumulated much more easily than in field studies (Zhang et al. 2003, White et al. 2009, Park 2012). This source of data, however, only offers an ecosystem-level perspective on phenology. Because the

resolution for the landcover data is 250 m, in most cases it cannot distinguish between the phenological patterns of individual species, making the approach only suitable for validation of herbarium-based models that aggregate phenological responses of multiple species (Park 2012). Because of the spatial and temporal limitations of expert field-observation datasets and the inability to identify different species in MODIS imagery-based data, neither of these approaches are very good for identifying the strengths and weaknesses of herbarium datasets.

Citizen science programs, partnerships between scientists and non-scientists to conduct authentic scientific research (Conrad and Hilchey 2011, Jordan et al. 2012), have also become increasingly used as a source of phenological data to investigate the growing array of global change questions (Vasseur et al. 2001, Morissette et al. 2009, Beaubien and Hamann 2011a, Hurlbert and Liang 2012, Wolkovich and Cleland 2011). Because citizen science volunteers typically span a diversity of backgrounds, age groups, and experience levels with scientific data collection, the quality of the data produced by citizen science efforts has been under scrutiny (Conrad and Hilchey 2011, Bonney et al. 2014). Substantial efforts have been made to investigate the quality of data collected by volunteers relative to the same data collected by professional scientists (McLaren and Cadman 1999, Engel and Voshell 2002, Fore et al. 2001, Newman et al. 2003, Foster-Smith and Evans 2003, Danielsen et al. 2005, Delaney et al. 2008, Crall et al. 2011, Danielsen et al. 2014). The general consensus among these studies is that citizen science projects with quality volunteer training, appropriate oversight, and easy data collection protocols (e.g. presence/absence data or counts rather than cover estimates or complicated species identification) produce data of comparable quality and accuracy to expert-generated datasets. Plant phenology citizen science programs such as the USA National Phenology Network (USA-NPN), Canada PlantWatch, Project BudBurst, and Global Learning and Observations to Benefit the Environment Program (GLOBE) have met these criteria by

monitoring easily identifiable species, using clear-cut categories for phenological phases (“phenophases”), providing high quality training opportunities, and offering ongoing communication and oversight for volunteers (Betancourt et al. 2007, Mayer 2010, Beaubien and Hamann 2011b, Denny et al. 2014). Datasets from all these programs have been used in studies that have stood up to rigorous scientific peer-review (Vasseur et al. 2001, Gazal et al. 2008, Morisette et al. 2009, Beaubien and Hamann 2011a, Wolkovich and Cleland 2011, Liang and Schwartz 2014).

Like satellite-based phenology datasets, the citizen science approach can cover large spatial scales and rapidly accumulate large quantities of data (Devictor et al. 2010). Like field-observation datasets made by professional scientists, citizen science also offers taxonomically discrete observations and random sampling of individual plants within sites. The citizen science approach also offers social benefits that other sources of validation data cannot provide, including increases in pro-environmental behaviors, scientific literacy, and sense of place among the volunteers (Brossard et al. 2005, Evans et al. 2005, Bonney et al. 2009, Crall et al. 2013; see Appendix A).

In this paper, we propose and test a novel method of using citizen science data to validate herbarium-based phenology models. We demonstrate this method using a research project that investigated the flowering phenology of an invasive plant (*Melilotus albus* Medik., “sweetclover”) relative to two native berry-producing plant species (*Vaccinium vitis-idaea* L., “mountain cranberry” or “lingonberry,” and *Vaccinium uliginosum* L., “bog blueberry”) that overlap in flowering times and share pollinators in the boreal forest. In experiments where the flowering times of these species fully overlapped, *M. albus* altered the pollinator community that services the berry species and increased seed production in *V. vitis-idaea* (Chapter 2). We expect that the extent of the overlap in flowering times would influence the strength of these

interactions. To look at variation in flowering overlap across the geographic ranges of these three species in boreal and arctic North America, we assessed the phenophases of > 2,100 herbarium specimens. We use data from a complementary citizen science program we developed in Alaska called the Melibee Project (“Meli” for *Melilotus*, and “bee” for the primary guild of pollinators it shares with the two *Vaccinium* species) to test and validate these models.

Of the general functions of biological models, system understanding, system control, and prediction (Haefner 2005), we are most interested in validating the herbarium models to offer system understanding. That is, we hope to determine whether the herbarium dataset is valid for investigating questions such as “has the time of flowering changed?” or “have there been greater shifts at high latitudes than at low latitudes?” Our future goal is to use the validated models to look at relative shifts in phenology between the focal species to identify locations where the flowering times might overlap the most. We explore three primary questions based on these validation goals for the methodological demonstration in this manuscript: 1) Are the models produced by the herbarium dataset valid for understanding relative differences in phenology through space and time? 2) Does adding geographic information improve the models compared to models using only date as a predictor variable? and 3) Can the models predict flowering dates for specific years and locations?

Herbarium-based model development

We retrieved *V. uliginosum*, *V. vitis-idaea*, and *M. albus* specimens from the herbaria at the University of Alaska Museum of the North, New York Botanical Garden, University of Washington Burke Museum, the Canadian Museum of Nature, University of Connecticut Torrey Herbarium, Royal Ontario Museum, University of Manitoba Herbarium, and Churchill Northern Studies Center. We limited our sampling effort to specimens that had reproductive structures present, both a date and location recorded, and occurred at 40 °N in latitude or higher in North

America (Figure 4.1). To reduce the influence of any one location on the models we randomly selected 5 data points for any location with > 5 data points. We assessed the reproductive phenophase of each specimen by counting the number of flower buds, open flowers, petal drops (flowers where petals have fallen off but the ovary has not yet swollen), immature fruits, and mature fruits on all individuals on the sample. Each reproductive phenophase was assigned a weight (1 = bud, 2 = flower, 3 = petal drop, 4 = immature fruit, and 5 = mature fruit). We then calculated a relative phenophase score for each sample by multiplying the number of reproductive structures counted for each phase by its phenophase weight and dividing by the total number of reproductive structures counted. Since by 31 September fruit at all locations was mature, we deleted data points with later dates. Final sample sizes were 835 for *V. uliginosum*, 863 for *V. vitis-idaea*, and 442 for *M. albus*.

From each specimen label, we collected date, latitude, longitude, and elevation as predictor variables. Using Google Earth (Google 2015), we geo-referenced each sampling location and collected two additional geographic variables that we expected to strongly influence phenology and climate: the distance to the nearest coastline of a major body of water (ocean, sea, or the Great Lakes) and whether location was on an island or not. For each species we used multiple regression to explain phenophase in terms of Julian date, the square of the Julian date (to allow for a non-linear relationship between date and phenophase), latitude, the interaction between Julian date and latitude, longitude, elevation, distance to nearest body of water, and whether it was on an island, and retained those variables included in the model with the lowest AIC score (Burnham and Anderson 2002). We also produced simpler models that included only Julian date and (Julian date)² (if retained following comparison of AIC scores).

Overall results for the herbarium models are shown in Table 4.1. As expected given the very large geographic area and long time period over which the data were collected, the models

explained relatively little (37-60%) of variation in phenophase, and in all cases Julian date contributed the highest partial R^2 . However, most geographic variables were retained in the models and together they accounted for an additional 3-7% of the variation.

Citizen science data collection

From 2011-2013, we established and operated the Melibee Project citizen science network with dual education/outreach and research goals. The education and outreach goals for the network were to 1) engage public participants in meaningful research on the impacts of invasive plants to an important subsistence food resource in Alaska, and 2) increase knowledge and awareness of invasive plants, climate change, reproductive ecology of plants, and scientific practices among the participants. We had two primary research goals: 1) provide a current snapshot of the flowering overlap of our three focal species across the state of Alaska, and 2) create an independent source of phenology data that could be used to validate the herbarium-based phenology models.

To achieve the education and outreach goals of the project, we recruited and trained volunteers from a diversity of communities and backgrounds throughout Alaska. We trained all volunteers through either a distance-delivery online training or an in-person workshop prior to commencing data collection. Training opportunities ranged in length from one hour to intensive 3-day workshops. Volunteers primarily consisted of families, K-12 educators & youth, environmental education camp participants, Alaska Native tribal and traditional council environmental programs, nature centers, land management agencies, and interested individuals. Approximately 250 volunteers actively participated in the research and submitted data. To achieve the research goals, we developed a phenology monitoring protocol that matched the manner in which we collected the phenology data from the herbarium specimens (Appendix B). During the summers of 2012 and 2013, volunteers selected one or more of the focal species

(sweetclover, blueberry or cranberry) to monitor and adopted 5 randomly selected reproductive individuals on which to quantitatively track phenology throughout the growing season. Once a week, or whenever possible, volunteers counted the number of flower buds, open flowers, petal drops, immature fruits, and mature fruits on each of their adopted plants. Data were submitted through an online portal (<http://www.handsontheland.org/environmental-monitoring/melibee-project.html>) or through direct communication with the research team. We ensured data quality by checking each submission for errors and by maintaining ongoing communication with volunteers to assist with any questions or complications that arose. Approximately 700 observations (which we defined as a set of counts on the five plants for each unique date and location) were submitted from 93 monitoring sites throughout Alaska (Figure 4.2). The general weather patterns in Alaska varied between the two years of citizen science data collection giving us the ability to detect model over- or under- prediction of the observed values due to a warmer than average or cooler than average year. The growing season (June-Aug) temperatures across the state were on average 0.6 °C cooler than the 30 year average in 2012, and 1.2 °C warmer than average in 2013 (Wendler et al. 2012, 2013).

For each of the 700 observations we calculated the phenophase score across the 5 adopted plants in the same manner as we did for the herbarium specimens. We collected geographic variables for each site (latitude, longitude, and elevation), and used Google Earth to collect the additional predictor variables used for the herbarium specimens (distance to nearest coastline and island status). Most sites provided < 10 data points per species; to prevent undue influence from sites at which a lot of data were collected we randomly selected 10 data points from any site with > 10 data points.

Model validation approach

We used regression analysis to compare the phenophase score predicted by the two herbarium-based models (the Julian date plus geographic predictor variables, referred to as the “geographic model;” and date + date² alone, the “date model”) with the actual observations made by the citizen scientists. As the maximum value a phenophase could have was 5, predicted values >5 were reassigned a value of 5. To directly compare the prediction ability of the date and geographic models for each species, we used a type I ANOVA including first the Julian date model and then the geographic model, and tested if it significantly improved the model to include the geographic variables.

To test whether developmental rates (time between phenophases) were estimated correctly, we evaluated whether the slope of the regression line differed from 1. To determine whether the model consistently over- or under-predicted phenophases for the citizen scientist data (i.e., whether date of initiation of flowering was accurately predicted), we tested whether the intercept differed from 0. For a measure of overall model prediction bias, we used the simultaneous F test for slope = 1 and intercept = 0 (Mayer and Butler 1993; Mayer et al. 1994; Haefner 2005). We also calculated the modeling efficiency (EF), an index of model fit that scales the model error to the variability of the observed data (Mayer and Butler 1993; Haefner 2005). Negative EF values indicate poor performing models, and EF values close to 1 indicate a near perfect fit to the observed data (Mayer and Butler 1993). We tested for prediction bias with changes in latitude using regression of the difference between the observed and predicted phenophase values against latitude.

Validating herbarium-based phenology models

For all three species there was a high correlation between the phenophases predicted from geographic herbarium models and actual phenophase scores collected by citizen scientists (V .

uliginosum: Pearson's $r = 0.84$, $n = 174$; *V. vitis-idaea*: $r = 0.88$, $n = 257$; *M. albus*: $r = 0.85$, $n = 80$; $P < 0.0001$ for all). Regression analyses indicated that for all 3 species the ability of the predicted phenophases based on herbarium data to explain the phenophases observed by citizen scientists was better than the ability of the date and geographic data to explain the herbarium data themselves (Tables 4.1 & 4.2, *V. uliginosum*: $R^2 = 0.70$ vs. 0.49 ; *V. vitis-idaea*: $R^2 = 0.78$ vs. 0.60 ; *M. albus*: $R^2 = 0.72$ vs. 0.37).

For *V. uliginosum*, the actual phenophases were slightly higher than the predicted values based on the geographic dataset (Table 4.2, Fig. 4.3A) but the y-intercept was not different from 0 ($P = 0.14$) and the slope was indistinguishable from 1 ($P = 0.15$). Overall model bias was significant for both the date model and the geographic model (Table 4.2). When separate regressions were run for 2012 and 2013, the y-intercept was not different from 0 in 2012 (intercept = 0.006 , $P = 0.98$) but marginally different in 2013 (intercept = 0.40 , $P = 0.06$), consistent with the prediction that plants should be more advanced in a warmer year. Furthermore, a comparison of the geographic model with the date model indicates that including geographic information in the model substantially improves the predictions (see bias and EF measures in Table 4.2; Fig. 4.3A vs. Fig 4.3B; type I ANOVA $F_{(1,171)} = 55.44$, $P < 0.0001$). This is consistent with our finding that *V. uliginosum* initiates flowering later at higher latitudes (significant latitude term in the geographic model) but also increases the rate of development of flowers to fruits as latitude increases (a significant date by latitude term). Neither the geographic model nor the date model had prediction bias with changes in latitude (date model: $F_{(1,172)} = 2.66$, $P = 0.11$; geographic model: $F_{(1,172)} = 1.44$, $P = 0.23$).

Results for *V. vitis-idaea* for the geographic model are similar to those for *V. uliginosum* (Table 4.2, Fig. 4.3C), with a slope indistinguishable from 1 ($P = 0.19$), but with a small, significantly positive y-intercept ($t_{(255)} = 3.25$, $P = 0.001$) indicating that the predicted values

consistently underestimated the observed values. Furthermore, the geographic model was not substantially better than the model based on dates alone at predicting phenophases (see bias and *EF* measures in Table 4.2; Fig. 4.3C vs. 4.3D; type I ANOVA $F_{(1,254)} = 3.18$, $P = 0.08$). The y-intercept was again greater in 2013 (0.32 vs. 0.13), but neither was distinguishable from zero ($P > 0.1$ for both). Both models produced less accurate predictions with increases in latitude (date model: $F_{(1,255)} = 5.41$, $P = 0.02$; geographic model: $F_{(1,255)} = 13.51$, $P = 0.0003$), but the predictions, on average, were off by less than 1 phenophase score (e.g. if the phenophase was predicted as flower, they were still being observed as in flower) at the highest latitude that was observed.

For *M. albus* the y-intercept of the geographic model was indistinguishable from zero and the slope was slightly greater than 1 (intercept $P = 0.28$, slope $P = 0.03$; Table 4.2, Fig. 4.3E). The geographic model was slightly better at predicting the observed phenophases than the model based on dates alone (see bias and *EF* measures in Table 4.2; Fig. 4.3E vs. 4.3F; type I ANOVA $F_{(1,77)} = 5.90$, $P = 0.018$). The y-intercept was again greater in 2013 than in 2012 (-0.10 vs. -0.51) but neither was distinguishable from zero ($P > 0.2$ for both). The geographic model showed a significant, but slight tendency for less accurate predictions with increasing latitude, while the date model did not (geographic model: $t_{(78)} = 2.31$, $P = 0.04$; date model: $t_{(78)} = 1.36$, $P = 0.18$).

Strengths and weaknesses of herbarium dataset

Using the citizen science data as an independent data source for model validation, we were able to investigate the strengths and weaknesses of the herbarium data set. Our demonstration suggests that phenology data from herbarium records can create valid models with respect to our primary modeling objective, understanding the system. This is suggested, first, by the consistent ability of the geographic models to accurately show the relative change in phenophase for all three species. Second, the geographic models were better able to explain the

phenophases observed by citizen scientists than the explanatory variables that contributed to the models were able to explain the phenophases of the herbarium data themselves. Historical herbarium records could indeed provide insight that is useful for addressing questions about the relative changes in plant phenology in a changing climate.

The herbarium-derived models we generated were not valid for accurate prediction of the phenophase for specific locations on a given date. For example, the *Vaccinium* spp. models all predicted the phenophase to be less advanced than what was actually observed, even in a relatively cool year (2012). *V. vitis-idaea* and *M. albus* geographic models also tended to produce less accurate predictions with increasing latitude. Further model calibration would be needed if predictions were the primary modeling goal. For two out of the three species we studied, the geographic data improved the ability to predict the citizen science observations compared to the date only models. This suggests that for most species it is worth the extra effort that is required to collect climate-related location data such as the distance to nearest coastline for each of the herbarium data points. This is consistent with other studies where climate-related corrections to herbarium-based phenology models were necessary to answer questions that address a large spatial scale (Lavoie and Lachance 2006). Using the number of growing degree days for the location (Euskirchen et al. 2014) or growing degree days since the disappearance of snow (Inouye and McGuire 1991) rather than Julian date would also likely improve the phenology predictions. Though labor intensive to gather this sort of fine scale data for each herbarium specimen, these measures help account for the variation in climate among the different years.

Applications and practical considerations

Our demonstration shows that citizen science plant phenology observations offer a novel source of data for validating herbarium-based phenology models that combines the benefits of

formerly used validation datasets (i.e. phenology data from field observations made by professional researchers or satellite imagery). The data are numerous and taxonomically discrete, can span vast geographic areas, and are collected using randomly selected plants. We foresee applications of this approach to a multitude of other research questions. For example, citizen science data could be used to validate other herbarium-based models that investigate the consequences of a changing climate, such as green-up or species distribution models. The strength of this approach is that the herbarium models are compared to a very high quality dataset that we expect to have relatively few errors. In addition, because data collection protocols can be standardized to match herbarium data protocols, evaluation can go beyond overall model fit and include specific questions (in this case, whether flower initiation and rate of development were estimated accurately).

The maintenance of a high quality citizen science program, even over a short time span, requires substantial effort and resources (Bonney et al. 2009). We were fortunate enough to be able to create a citizen science program that addressed our exact research questions, using protocols that we devised. Without substantive financial support, we would have been unable to recruit and train volunteers from such a broad geographic area, build the cyber infrastructure for volunteer data entry, or dedicate our time to ensure data quality, educational benefits for volunteers, and volunteer satisfaction. We believe, however, that pre-existing plant phenology citizen science networks with similar mechanisms that ensure data quality (e.g. USA-NPN, GLOBE, Canada PlantWatch, etc.) can be tapped to help alleviate this problem. Furthermore, advances in web-based technology and support structures for citizen science program development (e.g. CitSci.org or www.citizenscienceassociation.org) have made incorporating high quality citizen science into rigorous phenology research programs much more feasible than in the past (Miller-Rushing et al. 2012, Newman et al. 2012, Bonney et al. 2014).

Conclusions

The quantity of data available and the potential for large temporal and spatial scales to be covered by both herbarium records and citizen science observations make them rich resources for ecologists seeking insight into the nature of phenological change. Miller-Rushing et al. (2012) suggest that citizen science data used alongside other long-term phenology datasets such as herbarium records can lead to new scientific insights. We believe our approach using citizen science data to validate herbarium-based phenology models can help achieve this goal. We have found that the two types of data used together provide a powerful tool in the effort to use plant phenology as one of Earth's vital signs in a globally changing climate. By actively engaging citizens from many different communities in the research process, we believe the effects of such an approach may have amplifying benefits for enhancing public awareness of global change issues.

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Literature cited

- Badeck FW, Bondeau A, Bottcher K, Doktor D, Lucht W, Schaber J, Sitch S (2004) Responses of spring phenology to climate change. *New Phytologist* 162: 295–309
- Beaubien EG, Hamann A (2011a) Spring flowering response to climate change between 1936 and 2006 in Alberta, Canada. *BioScience* 61:515-524
- Beaubien EG, Hamann A. (2011b) Plant phenology networks of citizen scientists: recommendations from two decades of experience in Canada. *International Journal of Biometeorology* 55:833–841
- Betancourt JL, Schwartz MD, Breshears DD, et al. (2007) Evolving plans for the USA National Phenology Network. *Eos* 88: 211
- Bolmgren K, Lunnberg K (2005) Herbarium data reveal an association between fleshy fruit type and earlier flowering time. *International Journal of Plant Science* 166(4):663–670
- Bonney R, Cooper C, Dickinson J, Kelling S, Phillips T, Shirk JL (2009) Citizen science: a developing tool for expanding science knowledge and scientific literacy. *Bioscience* 59:977–984
- Bonney R, Shirk JL, Phillips TB, Wiggins A, Ballard HL, Miller-Rushing AJ, Parrish JK (2014) Next steps for citizen science. *Science* 343:1436-1437
- Brossard D, Lewenstein B, Bonney R (2005) Scientific knowledge and attitude change: The impact of a citizen science project. *International Journal of Science Education* 27:1099–1121
- Burnham KP, Anderson DR (2002) *Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach*, 2nd edn. Springer-Verlag

- Calinger KM, Queenborough S, Curtis PS (2013) Herbarium specimens reveal the footprint of climate change on flowering trends across north-central North America. *Ecology Letters* 16: 1037–1044
- CaraDonna PJ, Iler AM, Inouye DW (2014) Shifts in flowering phenology reshape a subalpine plant community. *Proceedings of the National Academy of Sciences* 111: 4916–4921
- Chaine I (2010) Why does phenology drive species distribution? *Philosophical Transactions of the Royal Society B* 365: 3149–3160
- Conrad, CC, Hilchey KG (2011) A review of citizen science and community-based environmental monitoring: issues and opportunities. *Environmental Monitoring and Assessment* 176:273–291
- Crall AW, Gregory J, Newman GJ, Stohlgren TJ, Holfelder KA, Graham J, Waller DM (2011) Assessing citizen science data quality: an invasive species case study. *Conservation Letters* 4:433–442
- Crall AW, Jordan R, Holfelder K, Newman GJ, Graham J, Waller DM (2013) The impacts of an invasive species citizen science training program on participant attitudes, behavior, and science literacy. *Public Understanding of Science* 22: 745-776.
- Danielsen F, Jensen PM, Burgess ND, Altamirano R, Alviola PA, et al. (2014) A multicountry assessment of tropical resource monitoring by local communities. *BioScience* 64: 236–251.
- Danielsen F, Burgess ND, Balmford A (2005) Monitoring matters: examining the potential of locally-based approaches. *Biodiversity Conservation* 14: 2507–2542
- Delaney DG, Sperling CD, Adams CS, Leung B (2008) Marine invasive species: validation of citizen science and implications for national monitoring networks. *Biological Invasions* 10:117–128

- Denny EG, Gerst KL, Miller-Rushing AJ, Tierney GL, Crimmins TM, Enquist CAF, et al. (2014) Standardized phenology monitoring methods to track plant and animal activity for science and resource management applications. *International Journal of Biometeorology* 58:591-601
- Devictor V, Whittaker RJ, Beltrame C (2010) Beyond scarcity: citizen science programmes as useful tools for conservation biogeography. *Diversity and Distributions* 16:354-362
- Engel SR, Voshell JR (2002) Volunteer biological monitoring: can it accurately assess the ecological condition of streams? *American Entomologist* 48: 164–177
- Estrella N, Sparks TH, Menzel A (2007) Trends and temperature response in the phenology of crops in Germany. *Global Change Biology* 13: 1737– 1747
- Euskirchen ES, Carman TB, McGuire AD (2014) Changes in the structure and function of northern Alaskan ecosystems when considering variable leaf-out times across groupings of species in a dynamic vegetation model. *Global Change Biology* 20:963–978
- Evans C, Abrams E, Reitsma R, et al. (2005) The Neighborhood Nestwatch Program: participant outcomes of a citizen-science ecological research project. *Conservation Biology* 19: 589–94
- Everill PH, Primack RB, Ellwood ER, Melaas EK (2014). Determining past leaf-out times of New England's deciduous forests from herbarium specimens. *Am J Bot* 101(8):1293-1300
- Fore LS, Paulsen K, O’Laughlin K (2001). Assessing the performance of volunteers in monitoring streams. *Freshwater Biology* 46: 109–123
- Forrest J, Miller-Rushing AJ (2010) Toward a synthetic understanding of the role of phenology in ecology and evolution. *Philosophical Transactions of the Royal Society B* 365:3101–3112.

- Foster-Smith J, Evans SM (2003). The value of marine ecological data collected by volunteers. *Biological Conservation* 113: 199–213
- Fridley JD (2012) Extended leaf phenology and the autumn niche in deciduous forest invasions. *Nature* 485: 359-362.
- Gallagher RV, Hughes L, Leishman MR (2009) Phenological trends among Australian alpine species: using herbarium records to identify climate-change indicators. *Aust J Bot* 57(1):1–9
- Gazal R, White MA, Gillies R, Rodemaker E, Sparrow E, Gordon L (2008) GLOBE students, teachers, and scientists demonstrate variable differences between urban and rural leaf phenology. *Global Change Biology* 14: 1568-1580.
- Google (2015) Google Earth, Version 7.1.2.2041 [Computer program]. Available at <http://www.google.com/earth/download/ge/...> (Accessed January 2015)
- Haefner JW (2005) Modeling biological systems: principles and applications. Springer, New York, New York
- Hart R, Salick J, Ranjitkar S, Xu J (2014) Herbarium specimens show contrasting phenological responses to Himalayan climate. *Proceedings of the National Academy of Sciences* 11:10615–10619.
- Hegland SJ, Nielsen A, Lazaro A, Bjerknes AL, Totland O (2009) How does climate warming affect plant-pollinator interactions? *Ecology Letters* 12: 184–195.
- Hulme PE (2011) Contrasting impacts of climate-driven flowering phenology on changes in alien and native plant species distributions. *New Phytologist* 189: 272–281.
- Hurlbert AH, Liang Z (2012) Spatiotemporal Variation in Avian Migration Phenology: Citizen Science Reveals Effects of Climate Change. *PLoS ONE* 7(2):e31662

- Inouye DW, McGuire AD (1991) Effects of snowpack on timing and abundance of flowering in *Delphinium nelsonii* (Ranunculaceae): implications for climate change. *American Journal of Botany* 78: 997-1001
- Jordan RC, Ballard HL, Phillips TB (2012) Key issues and new approaches for evaluating citizen science learning outcomes. *Frontiers in Ecology and the Environment* 10: 307–309
- Kadmon R, Farber O, Danin A (2003) Effect of roadside bias on the accuracy of predictive maps produced by bioclimatic models. *Ecological Applications* 14:401–413
- Kudo G (2014) Vulnerability of phenological synchrony between plants and pollinators in an alpine ecosystem. *Ecological Restoration* 29: 571–581.
- Lavoie C, Lachance D (2006) A new herbarium-based method for reconstructing the phenology of plant species across large areas. *American Journal of Botany* 93(4):512–516
- Liang L, Schwartz MD (2014) Testing a growth efficiency hypothesis with continental-scale phenological variations of common and cloned plants. *International Journal of Biometeorology* 58:1789-1797
- Mayer A (2010) Phenology and citizen science. *BioScience* 60:172-175
- Mayer DG, Butler DG (1993) Statistical validation. *Ecological Modelling* 68: 21-32
- Mayer DG, Stuart MA, Swain AJ (1994) Regression of real-world data on model output: an appropriate overall test of validity. *Agricultural Systems* 45: 93-104
- McLaren AA, Cadman MD (1999) Can novice volunteers provide credible data for bird surveys requiring song identification? *Journal of Field Ornithology* 70: 481–490
- Miller-Rushing A, Primack R, Bonney R (2012) The history of public participation in ecological research. *Frontiers in Ecology and the Environment* 10(6): 285–290

- Miller-Rushing AJ, Primack RB, Primack D, Mukunda S (2006) Photographs and herbarium specimens as tools to document phenological changes in response to global warming. *American Journal of Botany* 93(11):1667–1674
- Morisette JT, Richardson AD, Knapp AK, Fisher JJ, Graham EA, Abatzoglou J, Wilson BE, Breshears DD, Henebry GM, Hanes JM et al. (2009) Tracking the rhythm of the seasons in the face of global change: phenological research in the 21st century. *Frontiers in Ecology and the Environment* 7: 253–260
- Neil KL, Landrum L, Wu J (2010) Effects of urbanization on flowering phenology in the metropolitan phoenix region of USA: findings from herbarium records. *Journal of Arid Environments* 74(4):440–444
- Newman G, Wiggins A, Crall A, Graham E, Newman S, Crowston K (2012) The future of citizen science: emerging technologies and shifting paradigms. *Frontiers in Ecology and the Environment* 10(6): 298–304
- Newman C, Buesching CD, MacDonald DW (2003) Validating mammal monitoring methods and assessing the performance of volunteers in wildlife conservation- “Sed quis custodiet ipsos custodies?” *Biological Conservation* 113: 189–197
- Park IW (2012) Digital herbarium archives as a spatially extensive, taxonomically discriminate phenological record; a comparison to MODIS satellite imagery. *International Journal of Biometeorology* 56:1179–1182
- Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421:37-42.
- Penñelas J, Filella I (2001) Phenology – responses to a warming world. *Science* 294: 793.
- Penñelas J, Rutishauser T, Filella I (2009) Phenology feedbacks on climate change. *Science* 324: 887–888.

- Primack D, Imbres C, Primack RB, Miller-Rushing AJ (2004) Herbarium specimens demonstrate earlier flowering times in response to warming in Boston. *American Journal of Botany* 91(8):1260–1264
- Reddy S, Davalos LM (2003) Geographical sampling bias and its implications for conservation priorities in Africa. *Journal of Biogeography* 30:1719–1727
- Richardson AD, Keenan TF, Migliavacca M, Ryu Y, Sonnentag O, Toomey M (2013) Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. *Agricultural and Forest Meteorology* 169:156– 173.
- Robbirt KM, Davy AJ, Hutchings MJ, Roberts DL (2011) Validation of biological collections as a source of phenological data for use in climate change studies: a case study with the orchid *Ophrys sphegodes*. *Journal of Ecology* 99(1):235–241
- Sanchez-Fernandez D, Lobo JM, Abellan P, Ribera I, Millan A (2008) Bias in freshwater biodiversity sampling: the case of Iberian water beetles. *Diversity and Distributions* 14:754–762
- Schmidt-Lebuhn AN, Knerr NJ, Kessler M (2013) Non-geographic collecting biases in herbarium specimens of Australian daisies (Asteraceae). *Biodiversity Conservation* 22:905–919
- Schmidt-Lebuhn AN, Knerr NJ, Gonz lez-Orozco CE (2012) Distorted perception of the spatial distribution of plant diversity through uneven collecting efforts: the example of Asteraceae in Australia. *Journal of Biogeography* 39:2072–2080
- Vasseur L, Guscott RL, Mudie PJ (2001) Monitoring of spring flower phenology in Nova Scotia: comparison over the last century. *Northeast Naturalist* 8:393–402
- Visser ME, te Marvelde L, Lof ME (2012) Adaptive phenological mismatches of birds and their food in a warming world. *Journal of Ornithology* 153: 75-84.

- Wendler G, Moore B, Galloway K (2012) The climate of Alaska for 2012. Alaska Climate Research Center, Geophysical Institute, University of Alaska Fairbanks. Fairbanks, Alaska. [online] <http://climate.gi.alaska.edu/Statewide/2012/annual.html>
- Wendler G, Moore B, Galloway K (2013) The climate of Alaska for 2013. Alaska Climate Research Center, Geophysical Institute, University of Alaska Fairbanks. Fairbanks, Alaska. [online] <http://climate.gi.alaska.edu/Summary/Statewide/Annual/2013>
- White MA, DeBeurs KM, Didan K, Inouye DW, Richardson AD, Jensen OP, et al. (2009) Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982–2006. *Global Change Biology* 15(10):2335–2359
- Wolkovich EM, Cleland EE (2011) The phenology of plant invasions: a community ecology perspective. *Frontiers in Ecology and the Environment* 9: 287–294
- Zhang X, Friedl MA, Schaaf CB, Strahler AH, Hodges JCF, Gao F, Bradley C. Reed BC, Huete A (2003) Monitoring vegetation phenology using MODIS. *Remote Sensing of Environment* 84:471–475

Table 4.1 Results of the herbarium models. “Variables excluded” refers to variables not retained in the model. DTW is distance to nearest body of water. “ R^2 for date” refers to the sum of the partial R^2 for date + date² (if included in the model).

Species	N	Variables excluded	Model R^2	Model F	Model P	R^2 for date
<i>V. uliginosum</i>	832	island	0.49	114.51	<0.0001	0.42
<i>V. vitis-idaea</i>	863	date ²	0.60	186.08	<0.0001	0.55
<i>M. albus</i>	416	longitude, DTW, island	0.37	48.45	<0.0001	0.35

Table 4.2 Model validation linear regression and modelling efficiency index results for comparing the herbarium model predictions with phenophase values observed by citizen scientists. “Bias” indicates the simultaneous F-statistic for slope = 1 and intercept = 0. A significantly different intercept from 0, slope different from 1, or bias is indicated by a * ($P < 0.05$).

Species	Model	N	Linear Regression				Modelling efficiency <i>EF</i>
			R^2	Intercept estimate	Slope estimate	Bias ^a <i>F</i>	
<i>V. uliginosum</i>	Date	174	0.62	0.26	1.15*	29.13*	0.34
	Geographic	174	0.70	0.25	1.08	11.50*	0.57
<i>V. vitis-idaea</i>	Date	257	0.78	0.43*	1.02	12.33*	0.64
	Geographic	257	0.78	0.34*	1.05	11.76*	0.66
<i>M. albus</i>	Date	80	0.72	-1.03*	1.40*	1.02	0.65
	Geographic	80	0.72	-0.20	1.19*	0.71	0.67

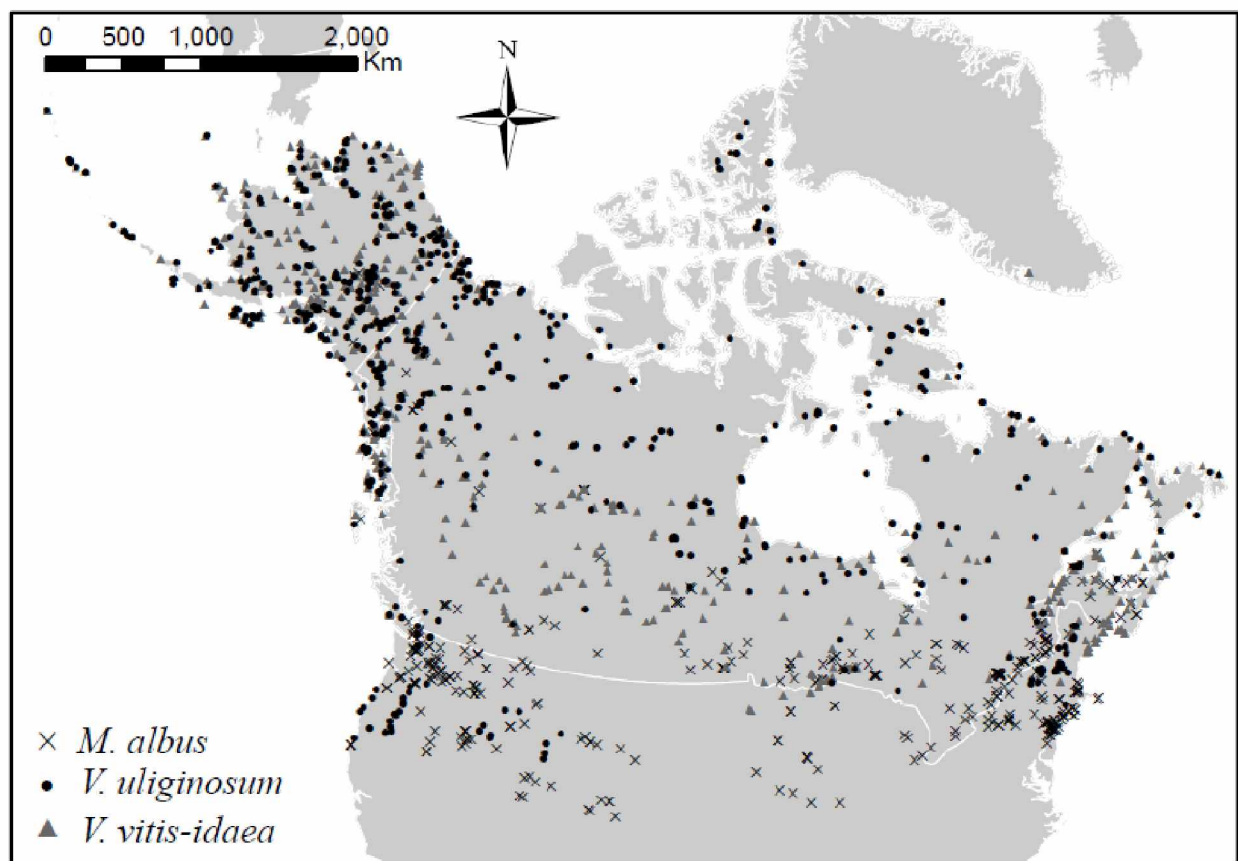


Figure 4.1 Herbarium sample distribution for *Melilotus albus* (416 specimens), *Vaccinium uliginosum* (835 specimens), and *Vaccinium vitis-idaea* (863 specimens).

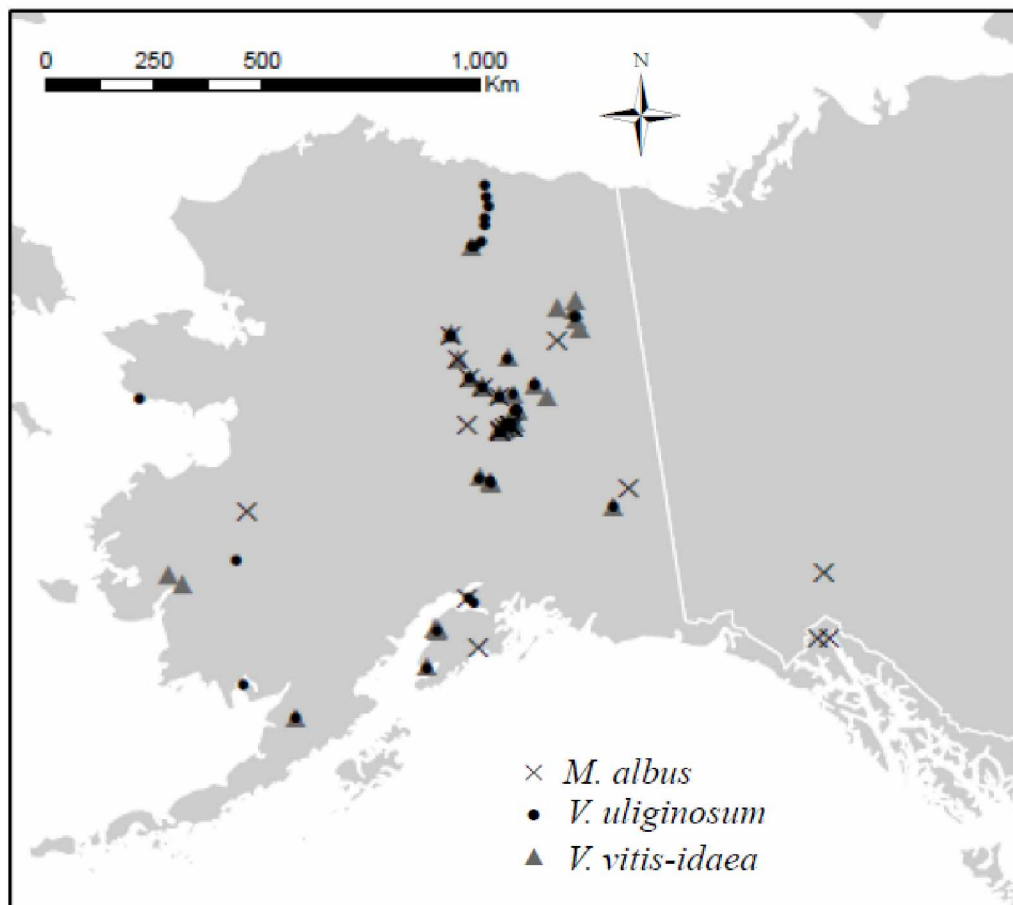


Figure 4.2 Phenology monitoring sites for the Melibee Project Citizen Science program across Alaska, USA.

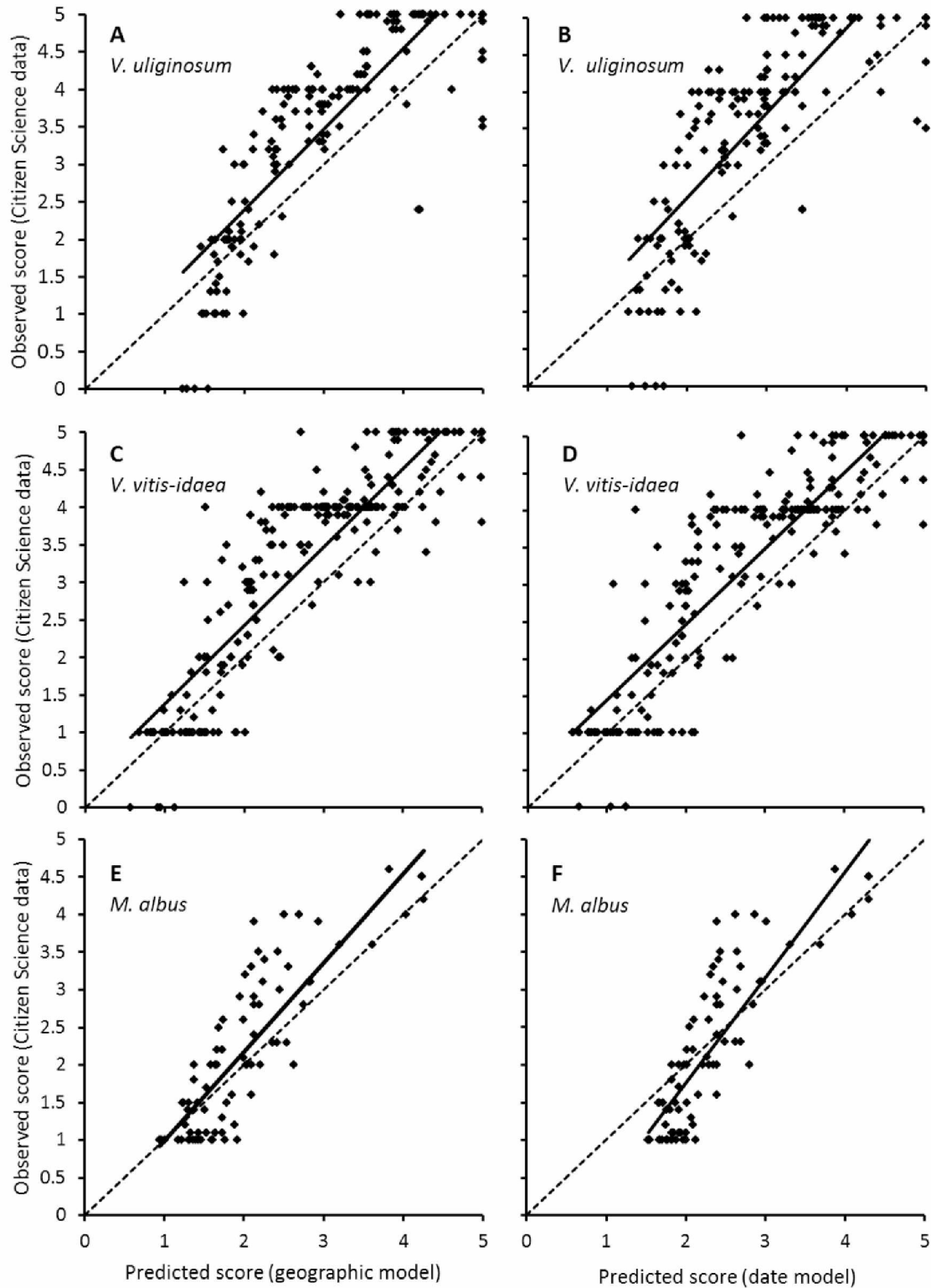


Figure 4.3 Regressions of observed data from the citizen science dataset against the predicted values (dark line) based on geographic models (left hand side) or date models (right hand side). Dotted line represents a line of perfect fit (1:1) for comparison.

CHAPTER 5

Metacognitive learning in the ecology classroom: a tool for preparing problem solvers in a time of rapid change?¹

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Abstract

Building communities that are resilient and adaptive to change requires the development of education strategies that train community members in higher order thinking skills that can be used to solve complex environmental problems. This study provides an empirical test of hypotheses within resilience theory that have suggested metacognitive learning strategies could increase resilience thinking skills such as scenarios thinking, systems thinking, and the ability to interpret and apply ecological data in complex problem solving. During a 6-week long ecology unit with 108 seventh grade students, we taught half the students using standard inquiry teaching methods and the other half using the same method, with the addition of a daily metacognitive learning intervention. We investigated the short-term (after six weeks of intervention) and long-term (one year after the intervention ended) effects of the intervention on student metacognitive ability and resilience thinking skills. Over the long term, we found a modest increase in the metacognitive ability of students who received the daily metacognitive journaling exercise. Interview data suggest that the structured metacognitive practice did most to improve the resilience thinking level of students who had low resilience thinking ability prior to the intervention period. However, the interaction between pre-treatment ability level and the treatment group was not detected in the written assessment data. These data suggest that the metacognitive learning intervention we used can benefit metacognitive ability over the long term, but has limited transferability to resilience thinking skills for most students. We suggest additional instructional practices for implementing metacognitive teaching approaches that could enhance the generalizability of their benefits across resilience thinking skills and student ability levels.

Keywords: adaptive capacity; education; metacognition; Metacognitive Learning Cycle; self-regulated learning; resilience; social-ecological systems.

Introduction

As the world undergoes rapid changes that affect people and ecology in interconnected ways, such as climate change, there is increasing motivation for society to enhance the resilience of social-ecological systems (Chapin et al. 2009). The social-ecological systems perspective holds that human and ecological dimensions of a system are not only linked, but co-evolving and shaping one another (Chapin et al. 2009). Resilience is the ability of the system to absorb rapid changes while maintaining essentially the same structure and function (Gunderson and Holling 2002). Building adaptive capacity, or the capacity of human actors to respond to or shape the consequences of change in a system, is often cited as a mechanism through which societies can enhance the resiliency of social-ecological systems (Folke et al. 2002, Adger et al. 2005, Gallopín 2006, Janssen and Ostrom 2006, Engle 2011). Adaptive capacity increases as groups and individuals gain the skills necessary to navigate change, such as flexibility, innovative and critical thinking, and the ability to form collaborative social networks (Chapin et al. 2009). In order to develop these sorts of skills, individuals and groups must have structured or scaffolded learning experiences (Argyris and Schön 1978, Senge 1990, Chapin et al. 2009, Kofinas 2009).

Social-ecological systems resilience is a rapidly growing field of interdisciplinary study that addresses the nature of social-ecological systems facing change, including how the system responds to, adapts to, learns from, or shapes change. Resilience and education researchers have begun to collaborate to investigate the roles learning and education play in navigating social-ecological change (Krasny et al. 2010). Recent research at the intersection of resilience and education has demonstrated the important role K-12 and post-secondary school systems play in increasing resilience and adaptive capacity in communities (reviewed in Muttarak and Lutz 2014). In 2010, the Ecological Society of America's Earth Stewardship Initiative called for

ecologists and ecology educators to articulate the science necessary for enhancing resilience and shaping social-ecological change (Chapin et al. 2011). With this call to action, it is increasingly relevant for ecology instructors to reflect on how their teaching practices can aid this effort. It is also increasingly important that science education researchers work with ecology instructors to implement and study evidence-based teaching practices that foster resilience.

Traditional education systems and K-16 ecology curricula have often not emphasized teaching strategies that improve higher order thinking skills necessary for solving social-ecological problems like climate change (D'Avanzo 2003a & b, Fazey et al. 2007, Tidball and Krasny 2011). Lower order thinking skills within Bloom's classic taxonomy include knowledge, comprehension, and application, while higher order thinking skills include analysis, evaluation, and synthesis or creation (Bloom et al. 1956, Anderson and Krathwohl 2001). Higher order thinking skills are not often taught in during ecology lessons (Brewer and Berkowitz 1998, D'Avanzo 2003a), primarily because of the instructional time they take away from covering required content (Blank 2000), the greater effort required to assess student learning in these skills (White 1993, Corliss and Linn 2011), and lack of pedagogical training of ecology educators (D'Avanzo 2003a). However, higher order thinking skills enable learners to use skills and knowledge in situations other than those in which the skill was learned and are therefore critical to solving problems in a rapidly changing world (Boddy et al. 2003, Fazey et al. 2007, Fazey 2010).

Several specific higher order cognitive abilities have been identified as key to building the collective ability of communities to adapt to and shape change (Box 1). These cognitive abilities include the ability to evaluate scientific information and concepts and apply it to novel situations (Carpenter 2002, Folke et al. 2003, Fazey et al. 2007), the ability to think critically to solve complex problems (Chapin et al. 2009, Fazey 2010), the ability to envision multiple

scenarios and prioritize most probable outcomes (MEA 2005, Mietzner & Reger 2005, Carpenter et al. 2006, Kofinas 2009), the ability consider both social and ecological aspects of a problem and how they interact (Sterling 2003, Kofinas 2009, Meadows 2008, Jordan et al. 2009, Krasny 2009, Crawford and Jordan 2013), the ability to think about future events or future desired ecological states and anticipate the consequences of present actions (Ascher 2009, Tschakert and Dietrich 2010, Tidball & Krasny 2011), and the ability to make bold decisions in the face of uncertainty (MEA 2005, Fazey et al. 2007, Chapin et al. 2009). Metacognition, or the knowledge of and ability to regulate one's own thinking, has been suggested as an important approach to learning that could help improve this suite of resilience thinking skills (Fazey et al. 2005, Fazey et al. 2007, Spellman 2015). Box 1 provides examples of these skills applied at the K-16 level and why metacognition would be expected to improve each of the resilience thinking skills.

Metacognition in education theory and practice

Metacognitive learning approaches emerge from self-regulated learning theory which contends that learning is governed by cognitive, metacognitive, and motivational aspects of a person and interacts with a person's beliefs and attitudes about themselves as learners, and with the larger learning environment (reviewed in Schraw et al. 2006). The connection between metacognition and learning was first suggested by Flavell (1979), who proposed that metacognition is a process of both monitoring and controlling thinking processes. Metacognition includes 1) personal knowledge or representations of the way a person thinks and learns in relation to other people or to tasks, goals, and activities, and 2) the knowledge and use of specific skills and strategies to accomplish or learn something (Efklides 2006). Several studies have shown that metacognitive experiences are crucial to learning processes and knowledge construction (Hewson and Thorley 1989, White and Gunstone 1989, Hennessey 1991, 1993, Baird et al. 1991, Beeth 1998), and that metacognitive ability and knowledge can be improved by

repeated practice throughout our lives (Brown and DeLoache 1978, Doran and Cameron 1995, Flavell et al. 1995). The strategic teaching of metacognition improves learning more than teaching content knowledge because students get practice learning how to learn rather than just accumulating facts (Schraw et al. 2006).

Several practical approaches have been developed for using metacognition in classroom settings, including interventions that involve self-reflective drawings (Wall et al. 2009), metaphors (Thomas and McRobbie 2001), collaborative group work (Hogan 1999, Larkin 2006), journaling (Hennessey 1991, 1993), portfolios (Nichols et al. 1997), and reflective reading (D'Avanzo 2003b). A broad and diverse body of empirical studies has demonstrated the benefits of metacognitive learning interventions in classroom settings (reviewed in Dignath and Büttner 2008). These benefits include longer-term retention and deeper understanding of science concepts (Blank 2000, Georgiades 2000, 2004), greater flexibility and innovation in how knowledge is learned and applied (Rickey and Stacy 2000, Rosencwajg 2003), improvement in reading comprehension (Loper and Murphy 1985, Brown and Palincsar 1989, Gourgey 2001) including reading on science topics (Yore et al. 1998, Koch 2001), improvement in academic achievement (Loper and Murphy 1985, Brown and Palincsar 1989), and increase in problem-solving ability (Carr and Jessup 1996, Stillman and Galbraith 1998, Zan 2000, Pugalee 2001, Schurter 2002, Kauffman et al. 2008).

Research context and questions

While the benefits of metacognitive learning strategies to student learning have been thoroughly established in the education literature, there remains a void in empirical evidence that the approach can directly improve the suite of key resilience thinking skills. There are very few studies on cognition or metacognition in ecology teaching and learning compared to fields like math, reading, and chemistry (D'Avanzo 2003b), and no study has yet investigated the effects of

metacognitive teaching methods on student ability to apply resilience thinking to solve problems that arise from rapid social-ecological change. Further, the problems social-ecological systems face span multiple disciplines, and nearly all the studies that investigate the impact of metacognition on learning have occurred within a single subject area such as math, science, or reading (Veenman et al. 2006). Several studies attempting to look across different learning domains have yielded inconclusive results. Some studies indicate that metacognitive skills are generalizable across learning domains and subject areas (Schraw et al. 1995, Schraw and Nietfeld 1998, Veenman and Verheij 2003, Veenman et al. 2004) while other studies suggest that different subjects and different types of tasks require different types of metacognitive activities (Glaser et al. 1992, Kelemen et al. 2000).

Our study used the issue of invasive plants in Alaska, the location of our study, as a context to test the effects of a metacognitive learning intervention on student resilience thinking and environmental problem-solving skills. Invasive plants are defined as non-native plants that spread rapidly and negatively impact ecosystems, the economy, or human health (U.S. Executive Order 13112, 1999). Invasive plants can alter ecosystem properties such as nutrient cycling, hydrology, and soil properties (reviewed in Skurski et al. 2014), affect the ecosystem services that sustain human well-being (e.g. water-filtration, food production, etc.; Pejchar and Mooney 2009), and impact the economy through high management costs (over \$35 billion dollars annually in the U.S. as of 2005; Pimentel et al. 2005). The spread of invasive plants in Alaska has rapidly accelerated in recent decades (Carlson and Shephard 2007). Increases in the number and extent of non-native species in Alaska may be attributed in large part to increases in human population and associated disturbances (e.g. more roads, resource extraction; Walker and Walker 1991; U.S. Census Bureau 2010; Carlson and Shephard 2007) and increased influx of propagules via imported agricultural and horticultural commodities (Conn et al. 2008). Climatic shifts in

Alaska such as warmer winters (Serreze et al. 2000) and longer growing seasons (Myneni et al. 1997) have also increased the likelihood of invasive plant success. The spread of invasive plants poses important social-ecological dilemmas that need to be addressed to manage ecological, cultural, and economic resources for future generations of Alaskans. For example, white sweetclover (*Melilotus albus* Medik.), one of the most widespread invasive plants in Alaska (AKEPIC 2014), out-competes native riparian plants for light (Spellman and Wurtz 2011), alters pollinator services to berry producing species that are used as a subsistence food resource (Spellman et al. *unpublished manuscript*), and is costly to manage (Schwörer et al. 2012). However, white sweetclover also provides an important nectar resource for honey producers in Alaska (Peterson 1989), which has presented a management conflict in some parts of the state. We use this and other similar invasive plant social-ecological dilemmas as a context for this study.

We chose to use a metacognitive intervention that has been found beneficial in the ecology classroom called the “metacognitive learning cycle” (Blank 2000). The metacognitive learning cycle model goes beyond the standard inquiry learning cycle model (Lawson et al. 1989, Bybee 1993, Allard and Barman 1994, Barman 1997, Boddy et al. 2003, Yager and Ackay 2010; Figure 1a) by providing structured, explicit opportunities for students to identify and reflect on their science ideas at every phase in the model (Blank 2000; Figure 1b). This is accomplished by student reflection on the status of their ideas, which includes the intelligibility, plausibility, and fruitfulness of their ideas (Hewson and Hewson 1988; Hewson and Thorley 1989, Henessey 1991, 1993). Henessey (1991, 1993) developed an intervention for accomplishing this task using journaling and peer discussion (Box 5.5). Students identify the intelligibility of their idea by putting the idea into words that make sense to them, then articulating it to someone else using examples. They evaluate the plausibility of the idea by relating the idea to their prior knowledge

or beliefs. The student reflects on the fruitfulness of their idea by thinking of ways the idea could help solve problems or be used for future learning or investigations (Henessey 1991, 1993).

In this study, we ask three questions: 1) Does the Metacognitive Learning Cycle intervention improve student metacognitive ability? 2) Does this metacognitive learning intervention affect the level of thinking across the suite of resilience thinking skills in a social-ecological problem solving context? and 3) Does the effect of the intervention vary with student ability level? We hypothesize that students who receive structured practice through the Metacognitive Learning Cycle reflective journaling intervention will improve their metacognitive ability (a response variable not tested in Blank's 2000 study) relative to students who do not receive the intervention. Further, we hypothesize that while teaching ecology through a local social-ecological issue, the students who receive the metacognitive intervention will be better able to apply resilience thinking skills in environmental problem solving than students who do not receive the intervention. The benefits of this technique may differ for students of different pre-treatment metacognitive or resilience thinking ability levels. Some people are already pre-disposed to metacognition (Fazey et al. 2007). People who are naturally reflective about their own learning in a variety of situations and are accepting of multiple perspectives tend to have an easier time practicing metacognition because the process is already automatic for them (Bransford et al. 2000, Fazey et al. 2005, Schwartz et al. 2005). Therefore, we hypothesize that students who perform high on pre-assessments of metacognitive and resilience thinking ability will show less initial gain from structured metacognitive practice than students for whom this sort of reflective learning is less well developed.

Methods

Study context and experimental design

This study was conducted in a public middle school in a small city in Alaska from August 2011 – December 2012. Six hundred and fifty students attend the school with 24% of the students eligible for free or reduced lunch, an indicator of relative poverty in the United States. Seventy-three percent of students are white, 9% two or more races, 8% Alaska Native, 5% Hispanic, 2% black, 1% Asian and 2% other (NCES 2012). The school was chosen for the study based on the willingness of a seventh grade life science teacher to participate in the project. The teacher taught four life science classes each day to a total of 108 students using the same content and activities. Seventh grade (students age 12-13) was selected as the focal grade level for the study due to the alignment of the social-ecological change context used in the study (the invasion of non-native plants in Alaska) with state and school district science curriculum requirements. The seventh grade curriculum at the time of this study included plant biology and ecology (FNSBSD 2009).

To provide a knowledge base about non-native plants and expose the students to the inquiry learning cycle model prior to beginning a metacognitive intervention experiment, the researcher (1st author) taught inquiry-based lessons on invasive plant ecology once or twice a week for 8 weeks. Social implications, including management applications, of the issues addressed in the lessons were also discussed. The lessons were aligned with and interspersed among general plant biology and ecology lessons taught by the teacher. The lessons used structured or guided inquiry through the 5E (Engagement, Exploration, Explanation, Elaboration, and Evaluation) learning cycle model (Figure 1a; cf. Bybee 1993, Boddy et al. 2003, Abrams et al. 2007, Blanchard et al. 2010) because it best fit the inquiry teaching model advocated by the Alaska Science Consortium and the pedagogical training of both the researcher and the collaborating science teacher.

Following the preliminary lessons, we used a quasi-experimental design to assess the effect of a structured six-week long metacognitive intervention on student metacognitive ability and resilience thinking skills. We refer to our design as “quasi-experimental” because of the small potential for students receiving the metacognitive intervention to discuss or use the metacognitive strategies in other classes where students from the control were present, thus “treating” them, too. The teacher and researcher continued to teach the range of required biology topics with a thread of invasive plant ecology and management supplementing the different topics. For two classes ($n = 52$ students), we continued instruction in same style of instruction as prior to the experiment, following the 5E inquiry learning cycle model (Figure 1a). This group is hereafter referred to as the “Inquiry” group. The other two classes ($n = 45$) were taught in the same manner as the inquiry group, but had a daily structured metacognitive journaling intervention (following Blank 2000, Hennessey 1993) added to the lessons (figure 5.5). The group of students receiving the metacognitive intervention is hereafter referred to as the “Metacognitive Inquiry” group. Both groups reflected daily on the concepts covered during the lessons, either in science notebooks or on lab handouts, for the last 5-7 minutes of the class period. The inquiry group had a single question posed by the teacher for journaling, while the metacognitive inquiry group followed the prescribed journal structure of the metacognitive “status” checks developed and tested by Hennessey (1993) and Blank (2000) (figure 5.5).

The inquiry and metacognitive inquiry groups were assigned to classes in a manner that balanced the academic ability of students falling within the two treatment groups as best as possible. We also considered the differences in student affect due to the time of day the class period fell that might influence the results, such as a class period early in the day or directly after lunch. We used the student’s 6th grade school district standards-based assessment (SBA) scores, which provides a categorical ranking for each student as “advanced,” “proficient,” or “below”

the expected grade-level performance in reading, writing, and math, to balance the overall academic ability level of the treatment groups. The periods assigned to the inquiry group had 19 advanced, 15 proficient, and 18 below students, while the metacognitive inquiry group had 12 advanced, 19 proficient, and 14 below students.

This study has a positivist-decontextualist orientation (Anderson et al. 2009), and is limited in the range of inferences that can be drawn about the nature of metacognition and student learning since it does not consider the broader learning landscape and ambiguities.

Assessment tools

We used three forms of assessment, discussed in detail below, to address our research questions: a metacognitive skills inventory, a resilience thinking written assessment, and semi-structured interviews. The metacognitive skills inventory and resilience thinking written assessment were both issued to all the participating students immediately prior to the intervention period (Pre-assessment) and immediately after six weeks of the intervention (Post-assessment). The interviews were conducted in the post-assessment phase only. To gauge the long-term effects of the treatment, both the metacognitive skills inventory and resilience thinking written assessment were given to a subset of the students 1 year after the intervention ended, when the students were in the 8th grade (Delayed Post-assessment; Inquiry n = 31, Metacognitive Inquiry n = 22).

Metacognitive skills inventory- The Metacognitive Activities Inventory (MAI) is a 27 item survey that was developed and validated to assess metacognitive skillfulness in problem solving by undergraduate science students (Sandí-Ureña 2008, Cooper and Sandí-Ureña 2009, Sandí-Ureña et al. 2011). Minor adaptations were made to increase ease of use for 7th graders, including reducing the 5-point Likert-scale to a dichotomous scale (yes/no) to allow for both the survey and written assessment to be completed within the time constraints of a single class

period, eliminating two of the original items that 7th graders had difficulty understanding, and slightly simplifying the vocabulary used (Appendix 5.1). Eighteen items were positively coded statements where an answer of “yes” indicated that the student engaged in a metacognitive activity. Seven items were reverse coded statements where an answer of “yes” indicated lack of engagement in metacognitive activity. To score the inventory, one point was assigned for every “yes” answer to positively coded items, and one point was assigned for every “no” answer to negatively coded items, for a maximum of 25 total points.

Resilience thinking written assessment- The resilience thinking written assessment (Appendix 5.2) and evaluation rubric (Appendix 5.3) were developed for this study to assess the complexity of discourse in each thinking skill in figure 5.4. The assessment included thirteen short answer problem-solving questions where students were asked to reflect on the ecological and social dimensions of change in two current invasive plants issues in Alaska. The first scenario looked at the social and ecological impact of invasive white sweetclover (*Melilotus albus*) on river floodplain ecosystems in Alaska (after Spellman and Wurtz 2011) and the second scenario asked the students to reflect on the impacts of white sweetclover on pollination of subsistence berries in Alaska (after Chapters 1 and 2; Appendix 5.2). Each problem solving scenario contained questions that targeted the seven resilience thinking skills identified in Figure 5.4.

A rubric to measure student progress across the suite of resilience thinking skills was created for this study in the style of a learning progression (cf. Mohan et al. 2009, Duschl et al. 2011). The complexity and sophistication of discourse in each thinking skill for each scenario was rated on a scale of 1 (low) to 5 (high) using the rubric in Appendix 5.3. Learning progression-style rubrics have been successfully applied to measure student progress in thinking skills in other studies (Ben-Zvi Assaraf and Orion 2005, Lee and Lui 2010). This style of rubric

is considered a highly credible way to measure higher order thinking processes and complex competencies in educational settings (reviewed in Jonsson and Svingby 2007). We defined the highest rubric level by the practices that would demonstrate mastery of the skill, such as discourse that included accuracy, innovation, and holistic thinking. In contrast, the lowest rubric level was defined by opposite tendencies in the discourse, such as inaccuracy, lack of innovation, and dualistic thinking. The constructs underlying each thinking skill in the rubric are intrinsically interrelated and each span vast literatures in their own right. Therefore, we focused the scoring criterion for each thinking skill on the specific elements within the thinking skill that distinguishes it from the other skills and restricted our interpretation of the skill to the particular attributes that the authors in Box 1 identified as key to social-ecological resilience. The specific assessment questions targeting each thinking skill were listed on the scoring rubric for reviewers to reference.

The assessments were blinded and randomized, then evaluated three separate times by three different reviewers. The reviewers were trained in the use of the rubric using a set of anchor assessments which were used as references to illuminate the differences between the score levels (cf. Moskal and Leydens 2000). Total written assessment scores were the sum of the rubric levels across all seven resilience thinking skills (cf. Box 1) for the two scenarios (maximum score = 70). Mean scores across the three assessment evaluators were used for analysis.

Resilience thinking interviews- Semi-structured interviews were conducted with 24 students. Two advanced, two proficient, and two below grade-level students (identified based on the SBA categorizations provided by the school district) were randomly identified from a stratified sample in each of the four classes for a total of 12 interviews from the inquiry group and 12 interviews from the metacognitive inquiry group. The interview content followed the

same criterion as the written assessment. It posed an invasive plant social-ecological problem-solving scenario based on current Alaskan research, the spread of invasive *Prunus padus* along salmon streams (based on Roon et al. 2014), and the 15 questions in the assessment targeted the resilience thinking skills in Box 1 (Appendix 5.4). Interviews lasted 15 to 20 minutes and were conducted over a period of two consecutive days. The interviews were digitally recorded for scoring at a later date. Two independent evaluators scored each interview using the same resilience thinking rubric as the written assessments. Total interview scores were the sum of the rubric levels across all seven resilience thinking skills (maximum score = 35). Mean scores across the two interview evaluators were used for analysis.

Analysis

Assessment and rubric validity and reliability

Four content experts examined and approved the assessment and rubric instruments for content validity and coherence with resilience thinking constructs proposed by authors in Box 1, including an ecology professor, a science education and outreach professor, a middle school life science teacher, and a doctoral candidate in a resilience theory-based PhD program. Oral interviews scored using the same rubric were used to cross-validate the assessment tool and address the potential for the rubric to indirectly measure student reading comprehension, written fluency, or writing ability. Correlation analysis was performed between the written assessment scores and interview scores to provide a measure of the rubric criterion and construct validity.

The inter-rater reliability of the written assessment was determined by calculating the mean rubric skill level across the seven thinking skills for each assessment, then comparing the number of agreements and adjacent agreements (within one rubric level) between each rater pair (AB, AC, and BC) using Cohen's weighted Kappa. The means of the agreement rate, the adjacent agreement rate, and the weighted Kappa of all rater pair combinations were used to

provide an overall inter-rater reliability measure. The mean correlation (Pearson's r) between each rater pair for total assessment scores was also calculated to provide an additional measure of assessment reliability. The reliability of interview assessment tool was measured in the same manner, but there were only two raters.

Metacognitive skills assessment and resilience thinking written assessment

We used the change in Metacognitive Activities Inventory and Resilience Thinking Written Assessment scores for individual students from the pre-intervention to the post-intervention assessment phases as our response variables. We tested for treatment effects, the effect of initial student ability level, and their interaction using Analysis of Covariance (ANCOVA). We used the score on the pre-assessments as the indicator of the pre-treatment student metacognitive ability or resilience thinking ability level. The same analysis was repeated to detect long-term changes in metacognitive abilities and resilience thinking using the change in assessment scores of a subset of students between pre- and delayed post-intervention phases. We also used Pearson's correlation to explore whether changes in resilience thinking ability were correlated with changes in metacognitive ability.

Resilience thinking interviews

We used a similar ANCOVA approach to test for the effects of treatment, initial student ability level, and their interaction on the resilience thinking interview assessment scores. Because we conducted the student interview only during the post-intervention assessment phase, we used the students' pre-intervention scores on the Resilience Thinking Written Assessment as a measure of the pre-treatment ability level in resilience thinking.

We performed all statistical analyses using SAS v.9.1 (SAS Institute, Cary, North Carolina).

Results

Assessment and rubric reliability and validity measures

The mean number of agreements between the three reviewers of the resilience thinking written assessment in the mean thinking skill level was 108 out of 252 assessments (43%; weighted Cohen's kappa = 0.40), and 229 assessment scores out of 252 were within one point of each other (91%). This level of agreement between three reviewers is considered reliable beyond what is expected by chance (Stoddart et al. 2000, Jonsson and Svingby 2007). Total assessment scores (sum of all thinking skill scores in both scenarios) were also consistent among the three reviewers (mean Pearson's $r = 0.70$). The mean number of agreements between the interview reviewers in the mean thinking skill level was 16 out of 24 interviews (67%; weighted Cohen's kappa = 0.73), and 100% were within one point of each other. Total interview scores were highly consistent between the two evaluators (Pearson's $r = 0.94$, $p = <0.0001$). The total scores of the written post-assessment and the interview for the 24 students interviewed were well correlated (Pearson's $r = 0.60$, $p = 0.002$), suggesting the scoring rubric did fairly well at evaluating the thinking skills independently of writing ability or fluency.

Metacognitive skills

There were no significant short-term changes in student self-reported metacognitive skills after the 6 week intervention period for the inquiry group or for the metacognitive inquiry group (Table 1, Figure 2a). One year after the treatment, however, the students who received the metacognitive intervention showed greater increases in their metacognitive ability than the students in the inquiry group, though the effect was only marginally significant (Table 1, Figure 2b). The student score on the Metacognitive Activities Inventory pre-test explained most of the variation in both the short-term and long-term change in scores (Table 1), with a significant negative relationship between pre-test scores and change in score for both assessment phases

(short-term: slope = -0.30, $p = 0.0009$; long-term: slope = -0.59, $p = <0.0001$). The relationship between student pre-scores and change in score did not vary between the two treatments for either time span (Table 1).

Resilience thinking skills in environmental problem solving

Students in the inquiry group had greater increases in Resilience Thinking Written Assessment scores over the 6 week intervention period than student who received the metacognitive intervention (Table 1, Figure 2c). This trend did not persist over the long-term in the sub-sample of students who completed delayed post-tests a year later (Table 1, Figure 2d). The pre-test scores on the Resilience Thinking Written Assessment had a strong influence on the change in score over both the short-term and the long-term (Table 1), with changes in scores decreasing with increasing pre-test scores (short-term: slope = -0.28, $p = <0.0001$; long-term: slope = -0.44, $p = 0.0003$). The treatment the student received did not affect the relationship between student pre-treatment ability level and change in resilience thinking ability over the short-term or the long-term (Table 1).

There was no correlation between short-term (pre- to post-) or long-term (pre- to delayed post-) changes in the Metacognitive Activities Inventory scores and Resilience Thinking Written Assessment scores (short-term: Pearson's $r = -0.11$ $p = 0.30$, $n = 89$; long-term: Pearson's $r = 0.07$, $p = 0.65$, $n = 47$).

Across all students interviewed, the treatment group could not explain variation in the resilience thinking scores of the interviewees, but there were significant pre-treatment resilience thinking ability and pre-treatment ability by treatment interaction effects (Table 1, Figure 3). The slope of relationship between pre-intervention resilience thinking written assessment scores and the interview scores was significantly less in the metacognitive inquiry group than the in the standard inquiry group (Figure 3).

Discussion

This study provides a contribution to both the metacognition research in science education and to the education research within social-ecological resilience theory and builds a bridge between the two bodies of research. First, we directly tested the effects of the Metacognitive Learning Cycle model (cf. Blank 2000) on student metacognitive ability and investigated the effect varied by the student's pre-existing metacognitive ability. Second, we provided an empirical test of the hypotheses within resilience theory that have suggested metacognitive learning interventions as an important strategy for increasing the adaptive capacity and resilience of communities dealing with rapid social-ecological system change.

Metacognitive skills

Students who received the metacognitive journaling intervention tended to have greater long-term improvement in their metacognitive inventory scores than students who received the standard inquiry instruction. The treatment effect was marginally significant, however. Despite this limitation to our study design, these data suggest that even a short exposure to structured metacognitive practice may produce lasting effects on student metacognitive skillfulness. This result is consistent with other studies which have found that seemingly minor metacognitive interventions can produce lasting impacts on student metacognition, learning processes, and achievement (Blank 2000, Thomas and McRobbie 2001, Dignath and Büttner 2008).

Resilience thinking ability

While there may be some long-term benefits to the structured metacognitive practice, we did not find strong evidence that most 7th grade students participating in our study were able to transfer these gains to resilience thinking. Contrary to what we expected based on empirical education research and resilience theoretical work (Box 1), Our results did not support the hypothesis that the metacognitive learning intervention we used improves student ability to use

resilience thinking skills in environmental problem solving. We offer some important considerations on the nature of the learning intervention we used and the characteristics of the students participating in this study that help explain this result.

The learning intervention we used, the Metacognitive Learning Cycle implemented through daily journaling and peer-discussion (cf. Hennessey 1991, 1993, Blank 2000), is only one among many metacognitive learning strategies that have been developed for K-12 and post-secondary classroom use (Nichols et al. 1997, Hogan 1999, Thomas and McRobbie 2001, D'Avanzo 2003b, Larkin 2006, Wall et al. 2009). Glaser et al. (1992) and Kelemen et al. (2000) found that different subjects and different types of tasks require different types of metacognitive activities. The intervention we used was developed in an ecology classroom. Different metacognitive teaching strategies or combinations of interventions may help students practice the diverse metacognitive skills needed to solve complex, multidisciplinary problems like the ones we posed in our resilience thinking assessments. By design, the resilience thinking assessments we developed required students to integrate ecology, social value systems, and natural resource management and targeted all seven of the resilience thinking skills in Box 1. Further research on the generalizability of different metacognitive skills across subject areas and learning domains and on the most effective interventions to target these skills, would greatly assist the assessment of the role metacognitive learning can play in social-ecological resilience.

Immediately after the 6-week intervention period, students who were taught with standard inquiry had improved their resilience thinking written assessment scores while students in the metacognitive inquiry group had not. The differences in resilience thinking ability between the treatment groups did not persist over the long term. Effective inquiry instructional methods alone can promote higher order thinking skills and implicit metacognitive reflection (Boddy et al. 2003, Yager and Ackay 2010). It is probable that if we had compared the metacognitive inquiry

or the guided inquiry methods we used in our treatment groups to ecology teaching strategies that did not offer opportunity for implicit or explicit metacognitive practice, such as passive lecture approaches (cf. D'Avanzo 2003b), we would have seen larger effect sizes between the treatment groups.

The age level of the students in this study may also have influenced our results. Several studies have suggested that metacognitive knowledge and skillfulness follow a developmental progression in school age students (Alexander et al. 1995, Kuhn 1999, Veenman et al. 2006, Wall 2008, Wall et al. 2009). Students age 12-13 were found to have the ability to think about their own learning processes and identify their learning strategies but had difficulty applying their metacognitive strategies to new learning situations (Wall et al. 2009).

Student ability level

Pre-existing metacognitive and resilience thinking ability level of a student was the most important predictor for both short and long-term changes in these skills. In both treatment groups, the students who scored low on pre-assessments improved their scores to a greater degree than students who scored in the mid or high ranges. Our interview data showed that explicit metacognitive practice may have had particular benefit to students at who had low initial ability to use resilience thinking skills in environmental problem solving. This result is consistent with prior research, which has indicated the importance of explicit metacognitive practice to under-achieving students (Veenman et al. 1994, Pressley and Gaskins 2006). Metacognitive capabilities begin to develop even in pre-school (Whitebread 1999) and students with early exposure to the relevance of metacognitive processes in their learning can spontaneously develop a metacognitive repertoire (Veenman et al 2006). Students who lack these sorts of conditions in their lives have a much more difficult time developing a metacognitive repertoire on their own, and show substantial learning gains when explicitly taught these strategies in the classroom

setting (Veenman et al. 1994, Pressley and Gaskins 2006). Our resilience thinking written assessment data did not show the same interaction between student ability level and treatment, suggesting that further research is necessary before making any general conclusions about the role metacognitive practice can play in improving the resilience thinking skills of students across a spectrum of abilities.

Increasing the impact of metacognitive learning on social-ecological problem solving

Several studies demonstrate that metacognitive reflection becomes more effective when teachers supplement metacognitive interventions with a few other practices: 1) teachers provide students with direct instruction about specific metacognitive strategies and the benefit it can have to their learning , 2) teachers provide students with feedback about their metacognitive practices, 3) teachers embed metacognitive instruction into content matter, and 4) teachers use metacognitive interventions for prolonged periods (Schraw 1998, Zimmerman 2002, Veenman et al. 2006, Dignath and Büttner 2008). Prior to beginning the intervention, we did not provide extensive instruction to the students about what constitutes metacognition or why it is important. We began implementing the intervention with a simple introduction on connecting new science ideas with ones they already have. Feedback on the metacognitive journaling intervention was limited to short comments while grading the science notebooks and brief interactions as the instructors circulated around the classroom while students completed the journal and peer-discussion prompts (Box 2). The feedback provided to students was very similar between the inquiry and metacognitive inquiry groups. Increased attention to these practices while implementing metacognitive learning strategies would likely improve the impact the intervention had on student resilience thinking and social-ecological problem solving.

The intervention in this study was implemented 30 times (daily for 6 weeks), which is in the mid-range of the metacognitive learning interventions used in studies that took place in

primary and secondary classrooms (ranged from 2 to 90 times; reviewed in Dignath and Büttner 2008). In a meta-analysis of metacognitive intervention studies, the more times an intervention was implemented the greater the effect size of the intervention (Dignath and Büttner 2008). Similarly, longer exposure to the metacognitive inquiry intervention may increase the impact it had on the resilience thinking skills. For the full benefits of metacognition on social-ecological problem solving, metacognitive processes need to become automated so the skills can be effectively transferred to other learning situations (Dignath and Büttner 2008) or unexpected states in a changing social-ecological system (Fazey et al. 2007). This highlights the importance of embedding metacognitive practice into classroom instruction throughout the educational process, from pre-K throughout post-secondary education. A diverse array of easily implemented metacognitive teaching approaches developed specifically for ecology courses to facilitate this at the college level is offered by D'Avanzo (2003b).

Ecology teachers have a special call to foster thinking skills in their students that help them use ecological knowledge for positive action (cf. Chapin et al. 2011). Further empirical research attempting to bridge education and resilience theory is increasingly important as we try to create learning environments that enable the world's citizens to productively navigate the unprecedented global changes we face.

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Literature cited

- Abrams, E., S. A. Southerland, and C. Evans. 2007. An introduction to inquiry. In E. Abrams, S. A. Southerland, and P. Silva (Eds.) *Inquiry in the classroom: Realities and opportunities*. Information Age Publishing, Greenwich, CT, USA.
- Adger, W. N., N. W. Arnell, and E. L. Tompkins. 2005. Successful adaptation to climate change across scales. *Global Environmental Change* 15: 77–86.
- AKEPIC -Alaska Exotic Plant Information Clearing House. 2014. AKEPIC Mapping Project Inventory Field Data. University of Alaska Anchorage Alaska Natural Heritage Program and USDA Forest Service, Anchorage, Alaska. Retrieved 9 September 2014 from <http://akweeds.uaa.alaska.edu/>
- Alexander, P. A., M. Carr, and P. J. Schwanenflugel. 1995. Development of metacognition in gifted children: Directions for future research. *Developmental Review* 15:1–37.
- Allard, D. W., and C. R. Barman. 1994. The learning cycle: A sound alternative to current college science teaching. *Bioscience* 44:99–101.
- Anderson, D., S. M. Nashon, and G. P. Thomas. 2009. Evolution of research methods for probing and understanding metacognition. *Research in Science Education* 39:181–195.
- Anderson, L. W., and D. R. Krathwohl. 2001. *A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives (complete edition)*. Longman, New York, NY, USA.
- Argyris, C. and D. Schön. 1978. *Organizational learning: a theory of action perspective*. Addison-Wesley, Reading, MA, USA.
- Ascher, W. 2009. *Bringing in the Future: Strategies for Farsightedness and Sustainability in Developing Countries*. University of Chicago Press. Chicago, IL, USA.

- Baird, J. R., P. J. Fensham, R. F. Gunstone, and R. T. White. 1991. The importance of reflection in improving science teaching and learning. *Journal of Research in Science Teaching* 28:163–182.
- Barman, C. 1997. The learning cycle revisited: A modification of an effective teaching model. Monograph 6. Council for Elementary Science International, Washington, DC, USA.
- Beeth, M. E. 1998. Teaching for conceptual change: Using status as a metacognitive tool. *Science Education* 83:343–356.
- Ben-Zvi Assaraf, O., and N. Orion. 2005. Development of system thinking skills in the context of earth systems education. *Journal of Research in Science Teaching* 42:518–560.
- Blanchard, M. R., S. A. Southerland, J. W. Osborne, V. D. Sampson, L. A. Annetta, and E. M. Granger. 2010. Is inquiry possible in light of accountability? A quantitative comparison of the relative effectiveness of guided inquiry and verification laboratory instruction. *Science Education* 94:577-616.
- Blank, L. M., 2000. A metacognitive learning cycle: a better warranty for student understanding? *Science Education* 84: 486-506.
- Bloom, B. S., M. D. Engelhart, E. J. Furst, W. H. Hill, and D. R. Krathwohl. 1956. Taxonomy of educational objectives: The classification of educational goals. Handbook 1: Cognitive domain. David McKay, New York, NY, USA.
- Boddy, N., K. Watson, and P. Aubusson. 2003. A trial of the Five Es: a referent model for constructivist teaching and learning. *Research in Science Education* 33(1):27-42.
- Bransford, J. D., Brown, A. L., & Cocking, R. R. (2000). *How People Learn: Brain, Mind, Experience, and School: Expanded Edition*. National Academy Press, Washington, DC, USA.

- Brewer, C. A., and A. Berkowitz. 1998. Preliminary results of the ESA survey on ecology in the undergraduate curriculum. *Bulletin of the Ecological Society of America* 79:106–07.
- Brown, A. L., and J. S. DeLoache. 1978. Skills, plans, and self-regulation. Pages 3-35 *in* R. S. Siegel, editor. *Children's thinking: What develops?* Erlbaum, Hillsdale, NJ, USA.
- Brown, A.L., & Palincsar, A.S. (1989). Guided, cooperative learning and individual knowledge acquisition. In L.B. Resnick (Ed.), *Knowing, Learning, and Instruction: Essays in Honor of Robert Glaser* (pp. 393–451). Erlbaum, Mahwah, NJ, USA.
- Bybee, R. 1993. An instructional model for science education. *In* *Developing Biological Literacy: a guide to developing secondary and post-secondary biology curricula:* Biological Sciences Curriculum Study, Colorado Springs, CO, USA.
- Carlson, M. L., and M. Shephard. 2007. Is the spread of non-native plants in Alaska accelerating? Pages 111-127 *in* T. B. Harrington and S. H. Reichard, editors. *Meeting the challenge: invasive plants in Pacific Northwest ecosystems*, General Technical Report PNW-GTR-694. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, USA.
- Carpenter, S. R. 2002. Ecological futures: building an ecology of the long now. *Ecology* 83: 2069-2083.
- Carpenter, S. R., E. M. Bennett, and G. D. Peterson. 2006. Scenarios for ecosystem services: an overview. *Ecology and Society* 11(1): 29.
- Carr, M., and D. L. Jessup. 1996. Cognitive and metacognitive predictors of mathematics strategy use. *Learning and Individual Difference* 7:235–247.
- Chapin, F. S. III, M. E. Power, S. T. A. Pickett, A. Freitag, J. A. Reynolds, R. B. Jackson, D. M. Lodge, C. Duke, S. L. Collins, A. G. Power, and A. Bartuska. 2011. Earth Stewardship: science for action to sustain the human-earth system. *Ecosphere* 2:89.

- Chapin, F. S. III, G. Kofinas, and C. Folke. 2009. Principles of ecosystem stewardship: Resilience for based resource management in a changing world. Springer, New York, NY, USA.
- Conn J. S., C. A. Stockdale, and J. C. Morgan. 2008. Characterizing pathways of invasive plant spread to Alaska: propagules from container-grown ornamentals. *Invasive Plant Science and Management* 1:331-336.
- Cooper, M. M., and S. Sandí-Ureña. 2009. Design and validation of an instrument to assess metacognitive skillfulness in chemistry problem solving. *Journal of Chemical Education* 86 (2): 240.
- Corliss S. B., and M. C. Linn. 2011. Assessing learning from inquiry science instruction. *In* G. Schraw and D. H. Robinson, editors. *Assessment of Higher Order Thinking Skills: Current Perspectives on Cognition, Learning and Instruction*. Information Age Publishing, Charlotte, NC, USA.
- Crawford, B.A., and R. Jordan. 2013. Inquiry, models, and complex reasoning to transform learning in environmental education. *In* M. E. Krasny and J. Dillon, editors. *Trading Zones in Environmental Education: Creating Transdisciplinary Dialogue*. Peter-Lang, New York City, NY.
- D'Avanzo C. 2003a. Research on learning: potential for improving college ecology teaching. *Frontiers in Ecology and the Environment* 1(10):533-540.
- D'Avanzo C. 2003b. Application of research on learning to college teaching: ecological examples. *Bioscience* 53:1121-1128.
- Dignath, C., and G. Büttner. 2008. Components of fostering self-regulated learning among students. A meta-analysis on intervention studies at primary and secondary school level. *Metacognition Learning* 3:231–264.

- Doran, C., and R. J. Cameron. 1995. Learning about learning. *Educational Psychology in Practice* 11(2):15–23.
- Duschl, R., S. Maeng, and A. Sezen. 2011. Learning progressions and teaching sequences: a review and analysis. *Studies in Science Education* 47: 123–182.
- Efklides, A. 2006. Metacognition and affect: What can metacognitive experiences tell us about the learning process? *Educational Research Review* 1:3-14.
- Engle, N. L. 2011. Adaptive capacity and its assessment. *Global Environmental Change* 21: 647–656.
- Fazey, I. 2010. Resilience and higher order thinking. *Ecology and Society* 15(3): 9.
- Fazey I., J. A. Fazey, and D. M. A. Fazey. 2005. Learning more effectively from experience. *Ecology and Society* 10: 4.
- Fazey, I., J. A. Fazey, J. Fischer, K. Sherren, J. Warren, R. F. Noss and S. R. Dovers. 2007. Adaptive capacity and learning to learn as leverage for social-ecological resilience. *Frontiers in Ecology and the Environment* 5: 375-380.
- Flavell, J. H. 1979. Metacognition and cognitive monitoring: a new area of cognitive developmental inquiry. *Cognitive Development* 34: 906–911.
- Flavell, J. H., F. L. Green, and E. R. Flavell. 1995. Young children's knowledge about thinking. *Monographs of the Society for Research in Child Development* 60(1): 1–95.
- FNSBSD- Fairbanks North Star Borough School District. 2009. 7th grade science curriculum: content standards and mastery core objectives. Fairbanks North Star Borough School District, Fairbanks, AK. http://www.k12northstar.org/sites/default/files/Gr_7_All.pdf
- Folke, C., S. Carpenter, T. Elmqvist, L. Gunderson, C. S. Holling, and B. Walker. 2002. Resilience and sustainable development: building adaptive capacity in a world of transformations. *Ambio* 31(5):437-440.

- Folke, C., J. Colding, and F. Berkes. 2003. Synthesis: building resilience and adaptive capacity in social-ecological systems. Pages 352-387 *in* F. Berkes, J. Colding, and C. Folke, editors. Navigating social-ecological systems: building resilience for complexity and change. Cambridge University Press, Cambridge, UK.
- Gallopín, G. C. 2006. Linkages between vulnerability, resilience, and adaptive capacity. *Global Environmental Change* 16: 293–303.
- Georghiades, P. 2004. Making pupils' conceptions of electricity more durable by means of situated metacognition. *International Journal of Science Education* 26: 85–99.
- Georghiades, P. 2000. Beyond conceptual change learning in science education: focusing on transfer, durability and metacognition. *Educational Research* 42: 119-139.
- Glaser, R., L. Schauble, K. Raghavan, and C. Zeitz. 1992. Scientific reasoning across different domains. Pages 345–371 *in* E. de Corte, M. C. Linn, H. Mandl, and L. Verschaffel, editors. Computer-based learning environments and problem solving. Springer Verlag, Heidelberg, Germany.
- Gourgey, A. F. 2001. Metacognition in basic skills instruction. Pages 17-32 *in* H. J. Hartman, editor. Metacognitive in Learning and Instruction: Theory, Research and Practice. Kluwer, Netherlands.
- Gunderson, L. H., and C. S. Holling. 2002. Panarchy: understanding transformations in human and natural systems. Island Press, Washington, DC, USA.
- Halpern, D. F. 1998. Teaching critical thinking for transfer across domains: Disposition, skills, structure training, and metacognitive monitoring. *American Psychologist* 53: 449-455.
- Hennessey, M. 1993. Students' ideas about their conceptualization: Their elicitation through instruction. Proceedings of the National Association for Research in Science Teaching annual meeting, Atlanta, GA, USA.

- Hennessey, M. 1991. Analysis of conceptual change and status change in sixth graders' concepts of force and motion. Doctoral dissertation, University of Wisconsin, Madison, WI.
- Hewson, P. W., and M. Hewson. 1988. An appropriate conception of teaching science: A view from studies of science learning. *Science Education* 72: 597–614.
- Hewson, P. W., and N. R. Thorley. 1989. The conditions of conceptual change in the classroom. *International Journal of Science Education* 11: 541–553.
- Hogan, K. 1999. Thinking aloud together: a test of an intervention to foster students' collaborative scientific reasoning. *Journal of Research in Science Teaching* 36:1085–1109.
- Janssen, M. A., and E. Ostrom. 2006. Resilience, vulnerability, and adaptation: A cross-cutting theme of the International Human Dimensions Programme on Global Environmental Change. *Global Environmental Change* 16:237–239.
- Jonsson, A., and G. Svingby. 2007. The use of scoring rubrics: reliability, validity and educational consequences. *Educational Research Review* 2:130–144.
- Jordan, R. C., S. A. Gray, M. Demeter, L. Lui, and C. Hmelo-Silver. 2009. Systems and cycles teaching ecology. *Applied Environmental Education and Communication* 8:40-48.
- Kauffman, D. F., X. Ge, K. Xie, and C. Chen. 2008. Prompting in web-based environments: Supporting self-monitoring and problem solving skills in college students. *Journal of Educational Computing Research* 38: 115-137.
- Kelemen, W. L., P. J. Frost, and C. A. Weaver III. 2000. Individual differences in metacognition: Evidence against a general metacognitive ability. *Memory and Cognition* 28: 92–107.
- Koch, A. 2001. Training in metacognition and comprehension of physics texts. *Science Education* 85: 758–768.

- Kofinas, G. P. 2009. Adaptive co-management in social-ecological governance. *In* F. S. Chapin III, G. Kofinas, and C. Folke, editors. Principles of ecosystem stewardship: Resilience for based resource management in a changing world. Springer. New York, NY, USA.
- Krasny, M. E. 2009. A response to Scott's concerns about the relevance of environmental education research: applying social-ecological systems thinking and consilience to defining research goals. *Environmental Education Research* 15:189–198.
- Krasny, M. E., C. Lundholm, and R. Plummer. 2010. Resilience in social-ecological systems: the roles of learning and education. *Environmental Education Research* 16:463–474.
- Kuhn, D. 1999. Metacognitive development. Pages 259-286 *in* L. Balter and C. S. Tamis-LeMonda, editors. Child psychology. A handbook of contemporary issues. Psychology Press, Philadelphia, PA, USA.
- Larkin, S. 2006. Collaborative group work and individual development of metacognition in the early years. *Research in Science Education* 36: 7-27.
- Lawson, A., M. R. Abraham, and J. W. Renner. 1989. A theory of instruction: Using the learning cycle to teach science concepts and thinking skills. NARST Monograph No. 1.
- Lee, H., and O. L. Liu. 2010. Assessing learning progression of energy concepts across middle school grades: The knowledge integration perspective. *Science Education* 94: 665–688.
- Linn, M. C. 2000. Designing the knowledge integration environment. *International Journal of Science Education* 22:781-796.
- Loper, A. B., and D. M. Murphy. 1985. Cognitive self-regulatory training for underachieving children. Pages 223-265 *in* D. L. Forrest-Pressley, G.E. Mackinnon, and T.G. Waller, editors. Metacognition, Cognition and Human Performance: Theoretical Perspectives, Vol. 2. Academic Press Inc., Orlando, FL, USA.

- MEA- Millennium Ecosystem Assessment. 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC, USA.
- Meadows, D. 2008. Thinking in Systems: A Primer. Chelsea Green Publishing, White River Junction, Vermont, USA.
- Mietzner, D., and G. Reger. 2005. Advantages and disadvantages of scenario approaches for strategic foresight. *International Journal of Technology Intelligence and Planning* 1:220-239.
- Mohan L., J. Chen, C. W. Anderson. 2009. Developing a multi-year learning progression for carbon cycling in socio-ecological systems. *Journal of Research in Science Teaching* 46:675-698.
- Moskal, B. M., and J. A. Leydens. 2000. Scoring rubric development: validity and reliability. *Practical Assessment, Research & Evaluation* 7(10).
- Muttarak, R. and W. Lutz. 2014. Is education a key to reducing vulnerability to natural disasters and hence unavoidable climate change? *Ecology and Society* 19(1): 42.
- Myneni, R. B., C. D. Keeling, C. J. Tucker, G. Asrar, and R. R. Nemani. 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* 386: 698-702.
- NCES- National Center for Education Statistics. 2012. North Pole Middle School, North Pole, Alaska <http://nces.ed.gov/ccd/>
- Nichols, S.E., D. Tippins, and K. Wiseman. 1997. A toolkit for developing critically reflective science teachers. *Research in Science Education* 27:175-194.
- Pejchar, L., and H. A. Mooney. 2009. Invasive species, ecosystem services and human well-being. *Trends in Ecology and Evolution* 24:497-504.
- Peterson, S. F. 1989. Beekeeping under the northern lights. *American Bee Journal* 129: 33-35.

- Pimentel, D., R. Zuniga, and D. Morrison. 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecological Economics* 52: 273-288.
- Pressley, M. and I. W. Gaskins. 2006. Metacognitively competent reading comprehension is constructively responsive reading: how can such reading be developed in students? *Metacognition Learning* 1: 99-113.
- Pugalee, D. K. 2001. Writing, mathematics, and metacognition: Looking for connections through students' work in mathematical problem solving. *School Science and Mathematics* 101: 236-245.
- Rickey, D., and A. M. Stacy. 2000. The role of metacognition in learning chemistry. *Journal of Chemical Education* 77:915-920.
- Roon, D. A., M. S. Wipfli, T. L. Wurtz. 2014. Effects of invasive European bird cherry (*Prunus padus*) on leaf litter processing by aquatic invertebrate shredder communities in urban Alaskan streams. *Hydrobiologia* 736: 17-30.
- Rosencwajg, P. 2003. Metacognitive factors in scientific problem-solving strategies. *European Journal of Psychology of Education* 18: 281-294.
- Sandí-Ureña, G.S. 2008. Design and validation of a multimethod assessment of metacognition and study of the effectiveness of metacognitive interventions. Doctoral dissertation. Clemson University, Clemson, SC.
- Sandí-Ureña, S., M. M. Cooper, and R. H. Stevens. 2011. Enhancement of metacognition use and awareness by means of a collaborative intervention. *International Journal of Science Education* 33: 323-340.
- Schraw, G. 1998. Promoting general metacognitive awareness. *Instructional Science* 2:113-125.

- Schraw, G., and J. Nietfeld. 1998. A further test of the general monitoring skill hypothesis. *Journal of Educational Psychology* 90: 236–248.
- Schraw, G., K. J. Crippen, and K. Hartley. 2006. Promoting self-regulation in science education: metacognition as part of a broader perspective on learning. *Research in Science Education* 36: 111–139.
- Schraw, G., M. E. Dunkle, L. D. Bendixen, and T. D. Roedel. 1995. Does a general monitoring skill exist? *Journal of Educational Psychology* 87: 433–444.
- Schurter, W. 2002. Comprehension monitoring: An aid to mathematical problem-solving. *Journal of Developmental Education* 26: 22–33.
- Schwartz, D. L., J. D. Bransford, and D. Sears. 2005. Efficiency and innovation in transfer. *In* J. P. Mestre, editor. *Transfer of learning from a modern multidisciplinary perspective: research and perspectives*. Information Age Publishing, Portland, OR, USA.
- Schwörer, T., R. Federer, and H. Ferren. 2012. Managing invasive species: how much do we spend? Technical report. Institute of Social and Economic Research, University of Alaska Anchorage, Anchorage, AK, USA.
- Senge, P. M. 1990. *The fifth discipline: the art and practice of the learning organization*. Doubleday Currency Press, New York, NY, USA.
- Serreze, M. C., J. E. Walsh, F. S. Chapin III, T. Osterkamp, M. Dyurgerov, W. C. Oechel, V. Romanovsky, J. Morison, T. Zhang, and R. G. Barry. 2000. Observational evidence of recent change in the northern high latitude environment. *Climatic Change* 46:159–207.
- Skurski, T. C., L. J. Rew, and B. D. Maxwell. 2014. Mechanisms underlying nonindigenous plant impacts: a review of recent experimental research. *Invasive Plant Science and Management* 7:432–444.

- Spellman, B. T., and T. Wurtz. 2011. Invasive white sweetclover (*Melilotus officinalis*) impacts native recruitment along rivers in interior Alaska. *Biological Invasions* 13:1779–1790
- Spellman, K. V. 2015. Educating for resilience in the north: building a toolbox for teachers. *Ecology and Society* 20(1): 46.
- Sterling, S. 2003. Whole systems thinking as a basis for paradigm change in education: explorations in the context of sustainability. PhD Dissertation. University of Bath, Bath, England.
- Stillman, G. A., and P. L. Galbraith. 1998. Applying mathematics with real world connections: metacognitive characteristics of secondary students. *Educational Studies in Mathematics* 36:157–189.
- Stoddart, T., R. Abrams, E. Gasper, and D. Canaday. 2000. Concept maps as assessment in science inquiry learning—A report of methodology. *International Journal of Science Education* 22:1221–1246.
- Thomas, G. P., and C. J. McRobbie. 2001. Using a metaphor for learning to improve students' metacognition in the chemistry classroom. *Journal of Research in Science Teaching* 38:222-259.
- Tidball, K. G., and M. E. Krasny. 2011. Toward an ecology of environmental education and learning. *Ecosphere* 2(2):21.
- Tschakert, P. & Dietrich, K.A. 2010. Anticipatory learning for climate change adaptation and resilience. *Ecology and Society* 15:11.
- U.S. Census 2010. Census 2010 Data for the State of Alaska. U.S. Census Bureau.
<http://www.census.gov/census2010/states/ak.html>

- Veenman, M. V. J. and J. Verheij. 2003. Identifying technical students at risk: Relating general versus specific metacognitive skills to study success. *Learning and Individual Differences* 13: 259–272.
- Veenman, M. V. J., B. H. A. M. Van Hout-Wolters, and P. Afflerbach. 2006. Metacognition and learning: conceptual and methodological considerations. *Metacognition Learning* 1: 3–14.
- Veenman, M. V. J., J. J. Elshout, and V. V. Busato. 1994. Metacognitive mediation in learning with computer-based simulations. *Computers in Human Behavior* 10:93–106.
- Veenman, M. V. J., P. Wilhelm and J. J. Beishuizen. 2004. The relation between intellectual and metacognitive skills from a developmental perspective. *Learning and Instruction* 14: 89–109.
- Walker, D. A., and M. D. Walker. 1991. History and pattern of disturbance in Alaskan arctic terrestrial ecosystems: a hierarchical approach to analysing landscape change. *Journal of Applied Ecology* 28:244-276.
- Wall, K. 2008. Understanding metacognition through the use of pupil views templates: pupil views of learning to learn. *Thinking Skills and Creativity* 3: 23-33
- Wall, K., S. Higgins, and L. Tiplay. 2009. Pupil views templates: exploring pupils perspectives of their thinking about learning. *In* Proceedings of the 1st International Visual Methods Conference, Leeds, UK, September 2009. International Visual Sociology Association.
- White, E. M. 1993. Assessing higher order thinking and communication skills in college graduates through writing. *Journal of General Education* 42:105-122.
- White, R., and R. Gunstone. 1989. Metalearning and conceptual change. *International Journal of Science Education* 11: 577–586.

- Whitebread, D. 1999. Interactions between children's metacognitive abilities, working memory capacity, strategies and performance during problem-solving. *European Journal of Psychology of Education* 14: 489–507.
- Yager, R.E., and H. Akcay. 2010. The advantages of an inquiry approach for science instruction in middle grades. *School Science and Mathematics* 110:5-12.
- Yore, L. D., M. T. Craig, and T. O. Maguire. 1998. Index of science reading awareness: An interactive-constructive model, test verification, and grades 4–8 results. *Journal of Research in Science Teaching* 35:27–51.
- Zan, R. 2000. A metacognitive intervention in mathematics at a university level. *International Journal of Mathematical Education in Science and Technology* 31:143–150.
- Zimmerman, B. J. 2002. Achieving academic excellence: A self-regulatory perspective. Pages 85–110 *in* M. Ferrari, editor. *The pursuit of excellence through education*. Lawrence Erlbaum, Mahwah, NJ, USA.

Table 5.1 ANCOVA results testing for the effects of student pre-treatment metacognitive or resilience thinking ability level, treatment (inquiry or metacognitive inquiry), and interaction on the change in Metacognitive Activities Inventory score, the change in Resilience Thinking Written Assessment score, and the total Resilience Thinking Interview score.

Response Variable	Source of Variation	df	Short-term (pre to post)			Long-term (pre to delayed post)		
			error df	<i>F</i>	<i>p</i>	error df	<i>F</i>	<i>p</i>
Change in Metacognitive Activities Inventory Score	Pre score	1	85	11.64	0.001	43	18.92	<0.0001
	Treatment	1		0.09	0.76		2.96	0.09
	Pre score * trt	1		0.02	0.87		0.35	0.56
Change in Resilience Thinking Written Assessment Score	Pre score	1	89	20.90	<0.0001	47	14.60	0.0004
	Treatment	1		4.92	0.03		0.29	0.59
	Pre score * trt	1		0.68	0.41		0.14	0.71
Resilience Thinking Interview Score	Pre score ¹	1	19	18.46	0.0004	.	.	.
	Treatment	1		0.94	0.34	.	.	.
	Pre score * trt	1		6.36	0.02	.	.	.

¹ The Resilience Thinking Interview was only conducted during the post-intervention assessment phase, and the Resilience Thinking Written Assessment pre score was used in the model to estimate student pre-disposition for resilience thinking.

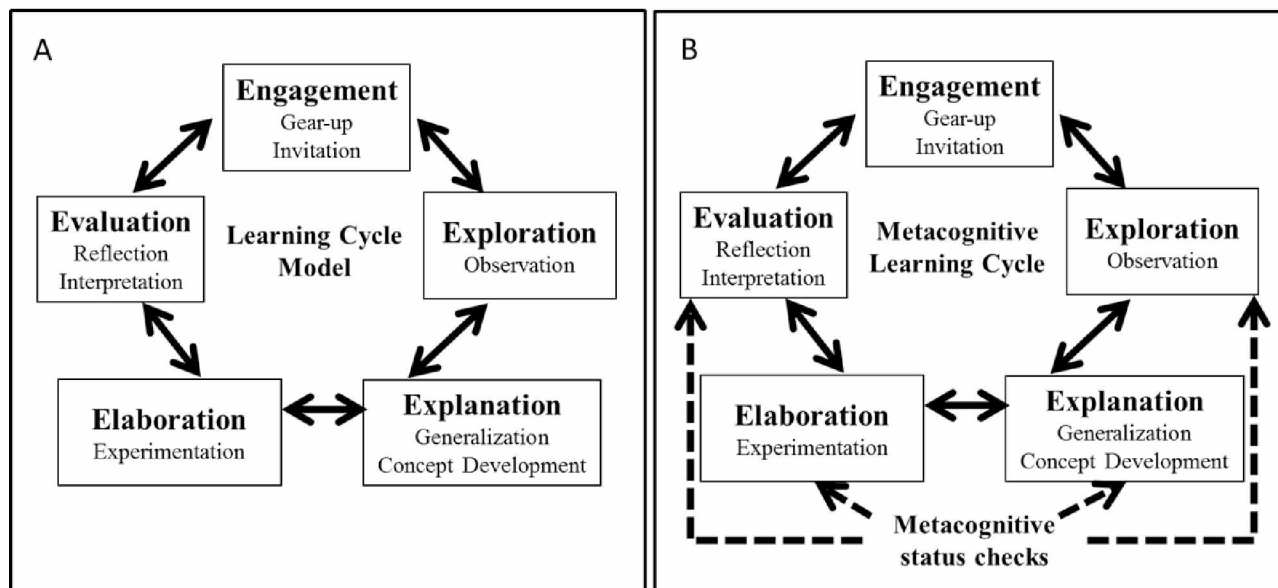


Figure 5.1 Comparison of the standard inquiry learning cycle model (A) and the metacognitive inquiry learning cycle model (B). The metacognitive learning cycle differs from the standard in that students are explicitly guided in conducting status checks of their own thinking at each step in the cycle. The terms for the inquiry phases in the 5E model (Engagement, Exploration, Explanation, Elaboration, and Evaluation) are in bold and alternate names used in other common version of the inquiry learning cycle model are listed below.

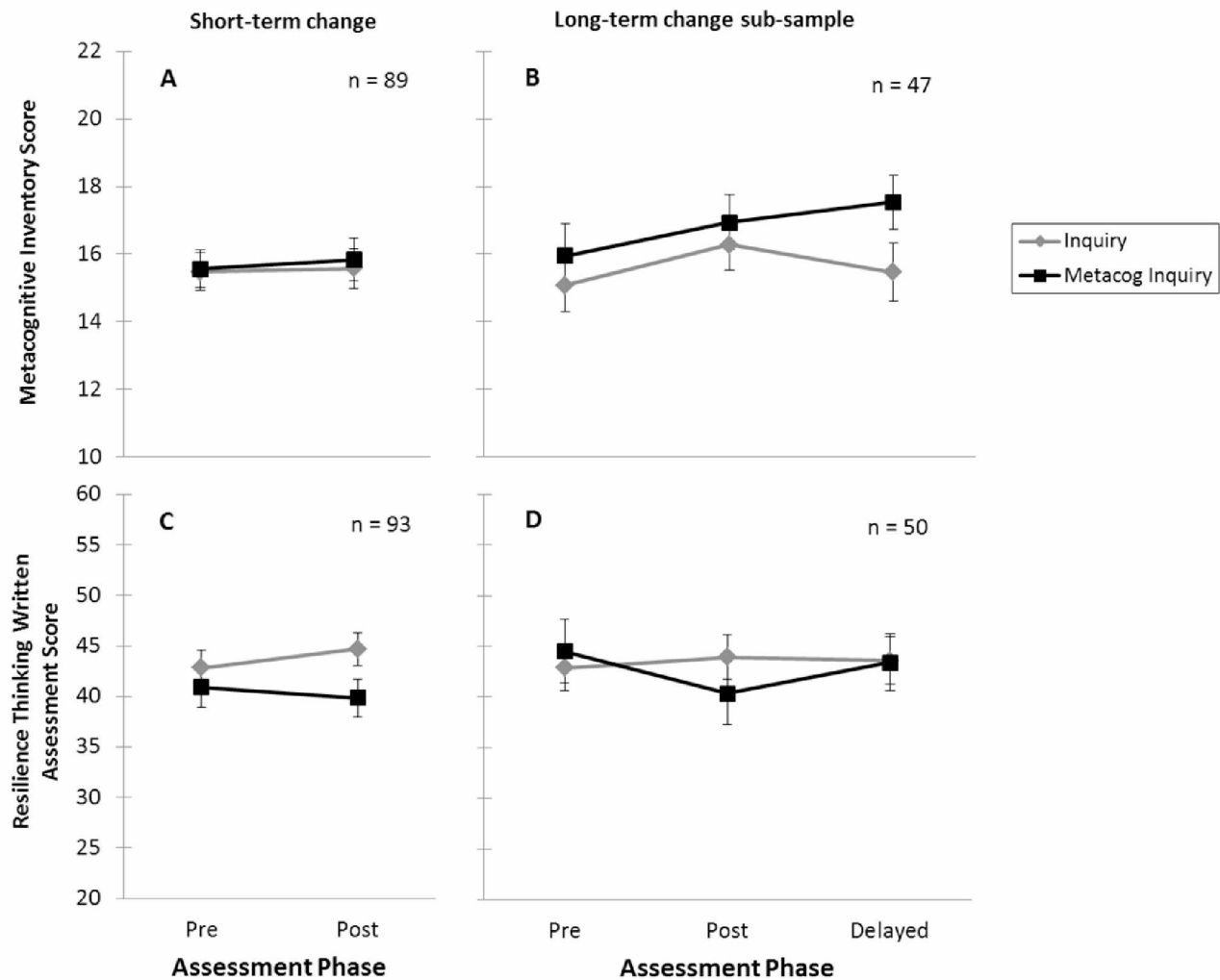


Figure 5.2 Metacognitive Activities Inventory (A, B) and Resilience Thinking Written Assessment (C, D) scores in the inquiry and metacognitive inquiry treatments for pre-, post-, and delayed post-intervention assessment phases. The short-term (the 6-week intervention period) change in scores (A, C) includes students who completed both pre- and post-tests, while long-term (one year later) change in scores includes only the sub-sample of students who completed pre-, post-, and delayed-post tests (B, D).

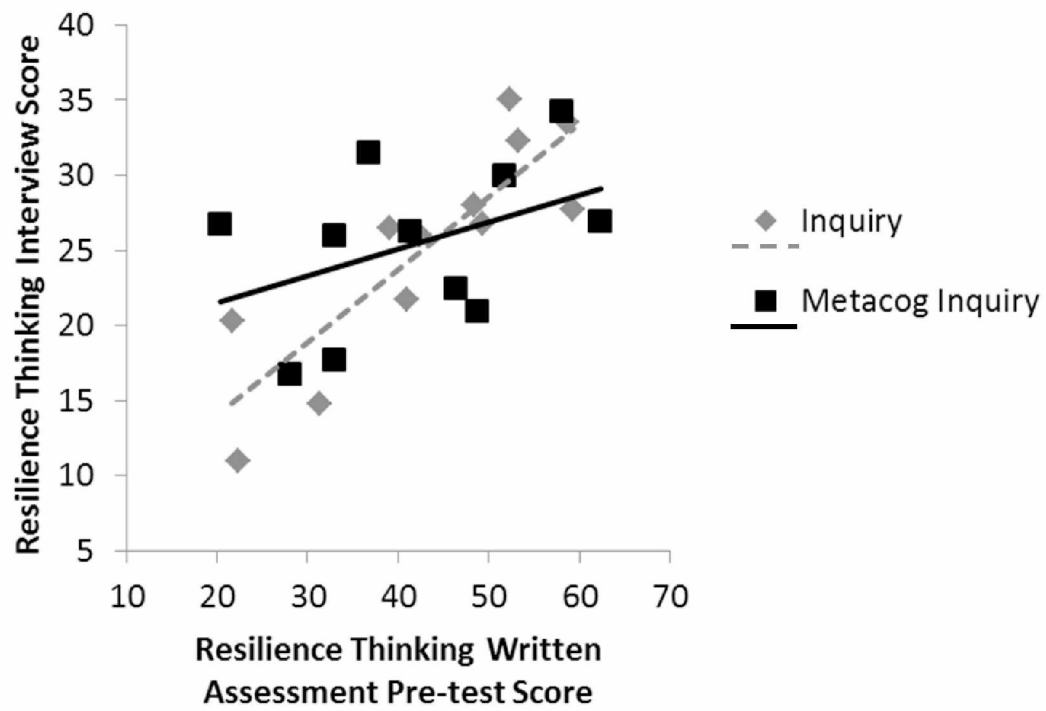


Figure 5.3 Relationship between Resilience Thinking Written Assessment pre-test scores and Resilience Thinking Interview scores for students in the inquiry and metacognitive inquiry treatment groups.

Figure 5.4 Potential effects of metacognitive learning on key thinking skills for individuals or communities prepared to navigate, adapt to, and shape change in social-ecological systems.

Ability to interpret scientific information (Carpenter 2002, Folke et al. 2003, Fazey et al. 2007)

Metacognitive learning improved the level of discourse on ecological topics and showed longer term retention of their ecology understanding than did students who learned through other approaches (Blank 2000).

Metacognition has also been cited as an important ability for students to be able to use science in novel contexts (Georghiades 2000).

Ability to apply new scientific information (Carpenter 2002, Fazey et al. 2007)

Studies in science classrooms and on learning in natural resource management teams suggest that metacognitive teaching approaches may be useful in enhancing student ability to apply knowledge flexibly and restructure existing knowledge when new scientific information becomes available (Rosencwajg 2003, Fazey et al. 2005)

Ability to think critically to solve complex problems (Chapin et al. 2009, Fazey 2010)

Critical thinking requires a variety of skills, including identifying sources of evidence for their thinking, analyzing the credibility of the evidence, assessing if the evidence fits within their prior knowledge, and using induction and deduction based on these steps to draw reasonable conclusions (Halpern 1998, Linn 2000). Many of these components of critical thinking require reflection on cognitive processes, or metacognition. It would be expected that structured, explicit metacognitive practice could improve the overall critical thinking ability of a student.

Ability to envision multiple scenarios and prioritize most probable outcomes (MEA 2005, Mietzner & Reger 2005, Carpenter et al. 2006, Kofinas 2009)

Scenarios thinking involves a process of creating multiple stories about possible futures based on a range of decisions in complex settings (Mietzner and Reger 2005). Metacognition has been demonstrated as a key skill in problem solving, which requires following multiple reflexive lines of thinking, or thought scenarios, toward a solution and refining thinking into a “best fit” solution (Rickey and Stacy 2000, Schraw et al. 2006).

Ability to view problems within a social-ecological system context (Sterling 2003, Kofinas and Chapin 2009, Meadows 2008, Jordan et al. 2009, Krasny 2009, Crawford and Jordan 2013)

Effective problem solving for resilience requires that individuals understand the interactions between system parts of entire complex systems, rather than considering single social or ecological aspects of a system, like poverty or biodiversity loss (Sterling 2003, Krasny 2009, Kofinas and Chapin 2009). Crawford and Jordan (2013) hypothesize that by using metacognitive strategies like thinking maps, where students illustrate a systems model of the connections between their ideas, students can gain improved understanding of larger systems like social-ecological systems.

Ability to think about future events or future desired ecological states and anticipate the consequences of present actions (Ascher 2009, Tschakert and Dietrich 2010, Tidball & Krasny 2011)

Metacognitive knowledge and skill increases by learning and experimentation with strategies and tasks that are oriented toward achieving some sort of future learning goal (Flavell 1979, Efklides 2006). It is reasonable to imagine that students practiced at imagining future states of their own knowledge and planning how to achieve those states, would also be able to transfer the skill to other situations such as envisioning future ecological states and anticipating the consequences of present actions.

Ability to make bold decisions in the face of uncertainty (MEA 2005, Fazey et al. 2007, Chapin et al. 2009)

In order for a social-ecological system to be resilient, decision makers within the system must be capable of guiding adaptation or transformation processes in the midst of uncertainty and surprises (MEA 2005, Fazey et al. 2007, Chapin et al. 2009). Metacognitive interventions ask students to call into question their own thinking and identify gaps in their knowledge (Schraw et al. 2006). These practices may improve student ability to identify sources of uncertainty, yet still be bold enough to propose a solution to a problem based on a solid line of reasoning.

Figure 5.5 Journaling exercise for students in being taught through standard inquiry learning cycle model (“Inquiry” group) and metacognitive learning cycle model (“Metacognitive Inquiry” group).

<p><u>Both control students and metacognition students</u></p> <p>What I think:</p> <p>Teacher poses one question from the day’s lesson. Students reflect on the question in their journal and write their ideas. <i>Example: We didn’t see any pollinators come to our plants today. Why do you think this happened?</i></p> <p><u>Explicit metacognitive intervention for metacognition students only</u> (Metacognition Status Checks developed by Hennessey 1991, 1993)</p> <p>How I know:</p> <p>The words make sense to me. (Circle one) Yes No</p> <p>I explained my idea to _____. (<i>Students explain their idea orally to the student sitting next to them</i>)</p> <p>My idea fits with other ideas that I know or evidence like:</p> <p>An idea that this question gives me for another investigation is: <i>or</i> My idea is important because it could help solve real-world problems like:</p>

Appendix 5.1 Metacognitive Activities Inventory (Sandí-Ureña 2008, Cooper and Sandí-Ureña 2009, Sandí-Ureña et al. 2011) modified for 7th grade. Coding for each item is indicated next to each statement.

Question	Coding	Statement
1	+	1. I read a problem carefully to fully understand it and figure out what the problem is really asking.
2	+	2. Before I answer a question, I try to think about the best way to write it out or say it.
3	-	3. When I solve problems, I think of my answer before I try thinking of why I think it is the answer.
4	+	4. I think about the steps of how I will solve a problem and decide if each step will really help.
5	+	5. I attempt to break down the problem to find the starting point.
6	+	6. I try to figure out the goal of a problem before attempting a solution.
7	+	7. I consider what information needed to solve a problem might be missing.
8	+	8. I check that the answer makes sense.
9	+	9. I feel creative and excited when I am solving problems.
10	+	10. Before attempting a solution, I take notes on things I know that might help me solve a problem.
11	+	11. I make sure that my solution actually answers the question.
12	-	12. I spend little time on problems that I have not been taught before.
13	+	13. I plan how to solve a problem before I actually start solving it (even if it is saying to yourself, "Okay, how am I going to do this?").
14	+	14. I think about things I know that are connected to a problem.
15	-	15. I spend little time trying to solve problems I am not sure I can solve.
16	-	16. I start solving problems without having to read all the details.
17	+	17. I try to figure out if there are connections between ideas or parts of a problem before trying to write a solution.
18	+	18. I try to relate new problems with previous situations I've been in or problems I have solved in the past.
19	+	19. I use graphic organizers (diagrams, flow-charts, etc.) to better understand problems.
20	-	20. If I do not know exactly how to solve a problem, I immediately try to guess the answer.
21	+	21. In word problems, I sort the information in the statement and determine what is important to answer the questions.
22	+	22. Once I figure out an answer, I check to see that if it agrees with what I expected.
23	-	23. Once I know how to solve a type of problem, I don't need to put any more time into understanding the concepts involved.
24	+	24. When I do homework problems, I try to learn more about the concepts so that I can apply this knowledge to test problems.
25	-	25. When practicing, if a problem takes several attempts and I cannot get it right, I get someone to do it for me and I try to memorize the steps.

Appendix 5.2 Resilience Thinking Written Assessment

Initials ____

A. Invasive plants and Food Webs:

Look at the diagram and graph below. Write scientific explanations for questions 1-5 on the next page.

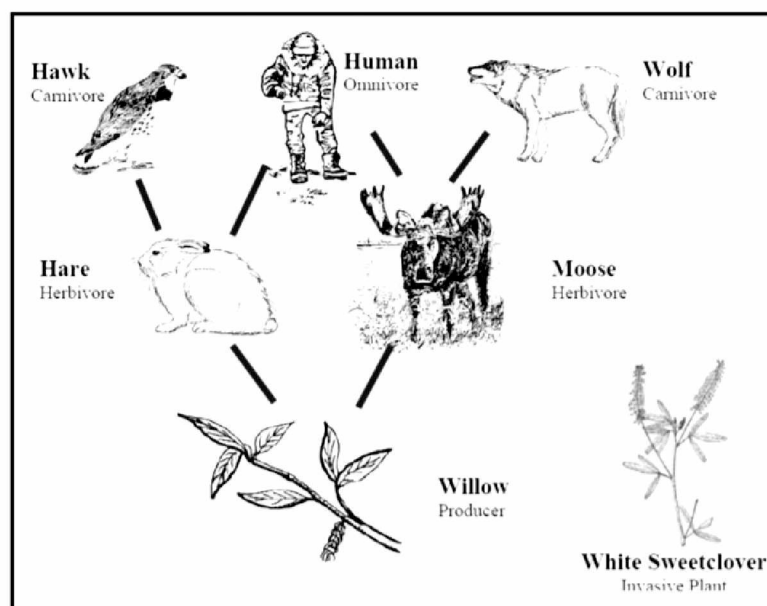


Figure 1. Food web for the Healy River floodplain in interior Alaska. Predator-prey interactions (who eats who) are represented by solid lines.

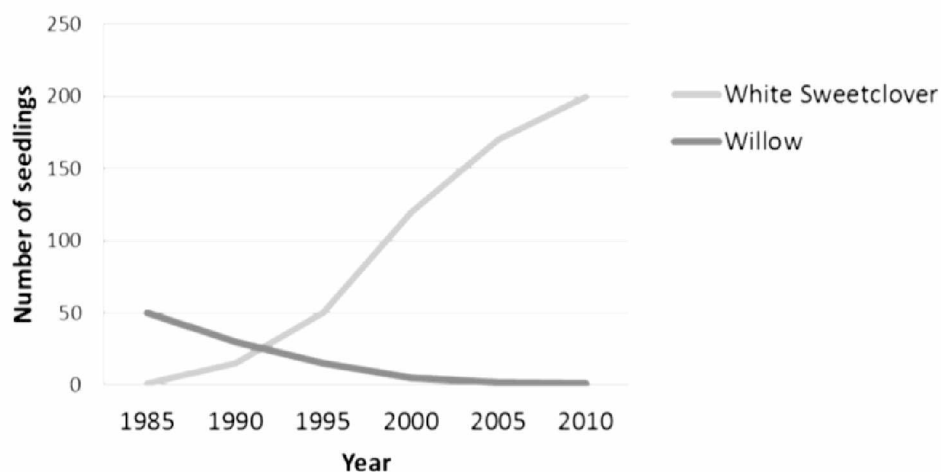


Figure 2. Average number of invasive white sweetclover (*Melilotus alba*) and native willow (*Salix* sp.) seedlings in 1 m² plots on the Healy River, Alaska from 1985-2010.

1. What happened to the willow as the number of white sweetclover seedlings increased?

2. If white sweetclover invaded a riverbank and spread over 25 years, what could happen to the moose?

3. Why do you think this would happen? What evidence did you use to come up with your idea in question 2?

4. Is there any other possible outcome for the moose besides that one you thought of? What else could happen to the moose?

5. Which outcome do you think is the most likely for the moose, your answer to 2 or your answer to 4? Why do you think so?

6. In the situation on page 2, what role, if any, could humans play in making sure that the Healy River food web remains stable in the face of white sweetclover invasion?

7. Imagine the following situation:

Invasive plant managers are concerned that white sweetclover is rapidly taking over the Healy River. They want to control the sweetclover by placing black tarps on the banks of the river. The black tarps block sunlight and super-heats the soil to kill seedlings and germinating seeds. By doing this, they will also kill the willow seedlings growing among the sweetclover. They plan on re-planting willows along the riverbanks after they remove the tarps in 3 years.



Figure 3. White sweetclover invasion on the Healy River, AK.

A team of scientists at the university just published a new scientific study that showed moose and hare populations on the Healy River are not affected by the white sweetclover. In fact, they found that both moose and hare are starting to eat the sweetclover.

Should the invasive plant managers carry out their plan to control the sweetclover by putting black tarps on the banks of the Healy River? Why or Why not?

B. Invasive plants and pollination



Native lowbush cranberry being pollinated.



Invasive white sweetclover being pollinated.

8. Both native cranberry plants and invasive white sweetclover need to be pollinated in order to produce seeds and fruits. Write one idea of what could happen to **pollination** if populations of the two plants were growing near each other?

9. What evidence could you use to test this idea? For example, if you designed an experiment, what would you observe or measure?

Imagine the following situation and answer questions 10-13:

You are a member of the North Pole City Council and you are trying to make a decision on whether or not to start a program removing the white sweetclover that grows near your town's favorite cranberry picking area.

You have read scientific studies that say white sweetclover can spread quickly in Alaska and impact ecosystems, but scientists do not yet know if the invasive plant can affect the pollination of cranberries in Alaska. You read many studies from other places to see what scientists have found out on this topic. Many studies showed that invasive plants can pull pollinators away from native plants, or outcompete them. A few studies, though, said that some invasive plants can actually bring more pollinators to an area. One study did not find any impact.

Table 1. Number of scientific studies that you read showing different impacts of invasive plants on the pollination of native plants.

Invasive plant impact	Number of studies finding this impact
Negative- Invasive plants pulling pollinators away from native plants. Native plants produce less berries or seeds.	20
Positive- Invasive plants increasing the pollinator populations by providing more food for them. Native plants benefit from more pollinators in the area.	5
No impact- Invasive plants do nothing to pollinators or native plants.	1

At the city council meeting, an invasive plant manager asked the city council to act quickly, because sweetclover spreads so rapidly. An elder who depends on collecting berries to cut her grocery costs asked the council to help protect important berry-picking land. A bee keeper asked the council to leave the sweetclover alone because his bees were using the plant to make honey.



Initials ____

10. The city council has gathered to take a vote and make a decision on whether or not to start the sweetclover removal program. Do you vote to start the sweetclover removal program?

11. What information did you use to make your decision?

12. Is there anything that you are uncertain about in the decision you made? If so, what additional information would you have liked to be more certain in your decision?

13. After you and the city council made the decision, some Alaskan scientists finish a study that shows the sweetclover does impact cranberry pollination and decreases the amount of fruit produced, but only for cranberry plants 5-10 meters away from the sweetclover. The berry plants further away are not impacted.

Do you change the decision you made in your answer to 10? Why or why not?

7

Scoring Rubric for Resilience Thinking Written Assessment

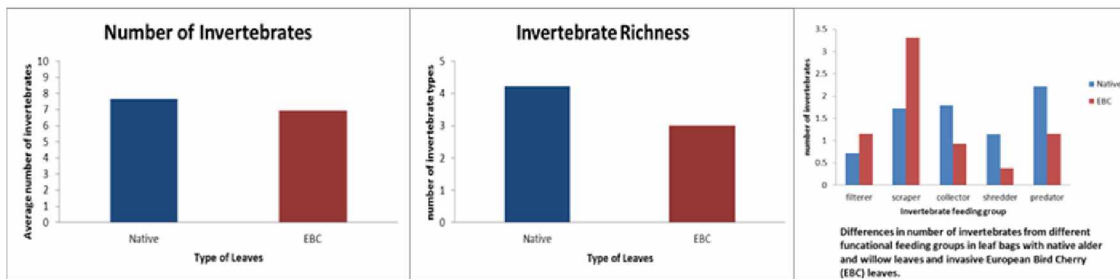
Resilience Thinking Skill	Scenario A questions targeting skill	Scenario B questions targeting skill	Level 5 (Upper Anchor)	Level 4	Level 3	Level 2	Level 1 (Lower Anchor)
Ability to interpret scientific information	1, 2	8, 9	Correct interpretation and understanding of scientific figures and tables or concepts addressed by question.	Mostly correct interpretation and understanding of information presented in figures and tables or concepts addressed by question.	Some understanding of information presented in figures and tables or concepts addressed by question.	Little understanding of information presented in figures and tables or concepts addressed by question.	No understanding of information presented in figures and tables or concepts addressed by question..
Ability to apply new scientific information	2, 7	13	Interprets and applies new information correctly, applies it in innovative ways.	Interprets and applies new information correctly.	Interprets new information correctly, somewhat applies it or applies it in not and entirely correct manner.	Interprets new information correctly, does not apply it.	Does not interpret new information correctly, does not apply new information to problem-solving or decision-making.
Ability to think critically to solve complex problems	3, 7	9, 11, 12	Illustrates a strong understanding of problem complexity; uses deduction and induction to propose a solution or decision on the presented problem.	Understanding of problem complexity; proposes a solution or decision, but unable to fully explain reasoning, or reasoning not fully based on evidence.	Understanding of problem complexity; proposes a solution or decision, but reasoning not based on evidence.	Some understanding of problem complexity; proposes a solution or decision, but unable to explain reasoning.	Problem is viewed as a black and white issue; problem solving or decision based on this dualistic view rather than inductive or deductive reasoning.
Ability to envision multiple scenarios and prioritize most probable outcomes	4, 5	12	demonstrates strong understanding of multiple scenarios or outcomes from a given situation or social-ecological context; uses evidence and reasoning to prioritize most probable outcomes.	demonstrates understanding of multiple scenarios or outcomes from a given situation; prioritizes most probable outcomes but reasoning is unclear.	able to envision other possible outcomes or scenarios from a given situation; able to prioritize outcomes but not able to explain reasoning.	somewhat able to envision other possible outcomes or scenarios from a given situation; unable to prioritize outcomes.	Unable to envision multiple scenarios or outcomes from a given situation; no prioritization of outcomes.
Ability to view problems within a social-ecological system context	6	11	Demonstrates strong understanding of problem in a system with multiple relationships between system parts; humans and ecosystem are an integrated system; understanding of constraining factors in the system (ex. Human livelihood and biological impacts of invasives must be considered to make a decision).	Demonstrates understanding of problem in a system with multiple relationships between system parts; humans and ecosystem are an integrated; some understanding of constraining factors in the system.	Demonstrates some understanding of relationships between system parts; humans and ecosystem are somewhat integrated; system constraints somewhat understood.	Recognizes few relationships between system parts; humans and ecosystem are somewhat integrated; system constraints not understood.	Human centered system or isolated ecological system; no connection to other systems or constraints.
Ability to think about future events or future desired ecological states and anticipate the consequences of present actions	6, 7	10	Uses causal relationships to anticipate future events, demonstrates understanding of human ability to act on an ecological issue, demonstrates why this action is important.	Uses causal relationships to anticipate future events, demonstrates understanding of human ability to act on an ecological issue, but has an incomplete understanding of why this action is important.	Demonstrates some understanding of how human action can effect future events or ecological states, uses incomplete reasoning to explain what these future states might be; has incomplete understanding why this action is important.	Demonstrates little understanding of how human action can effect future events or ecological states; does not explain what these future states might be; has little understanding why this action is important.	Demonstrates no connection between human actions and future ecological states or future events.
Bold decision making in the face of uncertainty	7	10, 15	Able to make a well-reasoned decision with information available; Able to identify sources of uncertainty in decision making and further information needs.	Uses information available to make a decision, reasoning is mostly clear; Able to identify sources of uncertainty or further information needs.	Uses information available to make a decision, but reasoning is not clear. Somewhat able identify sources of uncertainty or further information needs.	Makes a decision, but reasoning is not clear and is not based on the available information. Somewhat able identify sources of uncertainty or further information needs.	Unable to explain decision-making; unable to identify sources of uncertainty in decision making or further information needs.

Appendix 5.4 Resilience Thinking Interview

Name _____ Date _____ Period _____

Recording file name _____ interview length _____

1. Take a look at the graphs of results from our class study on the impact of invasive European bird cherry on stream habitats. What do these graphs mean? What do they tell us about our study results?



2. A scientist named Dave Roon did this same study in Anchorage in a salmon stream in downtown Anchorage. He got different results than us. He found that European bird cherry leaves did not affect the number or the kinds of stream invertebrates in his leaf bags.

- Whose results do you trust? Why?
- Why do you think he got different results?
- Is there anything that you have observed or thought about that provides evidence that you are right? How does that evidence show that your reasoning is correct?
- Could you suggest an experiment or investigation different than the one we completed in class that would show whether you are right?
- What would you expect the results of your investigation to be? How would those results show that you are right?

3. In Fairbanks and North Pole, people really love European bird cherry. My mom and dad have one in their yard. It is one of the only trees that can grow in Fairbanks that has beautiful blossoms in the spring. It is really beautiful. Stores and greenhouses sell it, and it makes them a lot of money. We saw in our study, though, that European bird cherry can change stream habitats. Bird cherry has begun to spread rapidly along streams in Alaska. A lot of it has spread on the Chena River.

- Is there anything humans can do about this conflict?

- b. What should we do?
- c. If you get rid of the bird cherry, what do you tell the people who love it, and the people who make money off of it?
- d. If you keep the bird cherry, what do you think will happen to the stream habitats?
- e. Can you think of a way to solve this problem so that people and stream habitats both end up in a good state?
- f. How much confidence do you have that this solution would work? What makes you uncertain about the plan? What could change without your control?
- g. If people listened to your solution, do you think this solution would work a long time from now, say, 30 years from now? Why do you think so?
- h. What would happen in 30 years if they didn't listen to your solution?
- i. Would you change your idea after thinking about it from a more long-term perspective?

Appendix 5.5 University of Alaska Fairbanks Institutional Review Board research approval letter.



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Institutional Review Board

909 N Koyukuk Dr. Suite 212, P.O. Box 757270, Fairbanks, Alaska 99775-7270

November 2, 2011

To: Laura Conner
Principal Investigator
From: University of Alaska Fairbanks IRB
Re: [275589-2] Metacognitive Learning in the Middle School Biology Classroom: a tool for preparing problem solvers in a time of rapid ecological change?

Thank you for submitting the Amendment/Modification referenced below. The submission was handled by Expedited Review under the requirements of 45 CFR 46.110, which identifies the categories of research eligible for expedited review.

Title:	Metacognitive Learning in the Middle School Biology Classroom: a tool for preparing problem solvers in a time of rapid ecological change?
Received:	October 28, 2011
Expedited Category:	7
Action:	APPROVED
Effective Date:	November 2, 2011
Expiration Date:	November 2, 2012

This action is included on the November 17, 2011 IRB Agenda.

No changes may be made to this project without the prior review and approval of the IRB. This includes, but is not limited to, changes in research scope, research tools, consent documents, personnel, or record storage location.

CHAPTER 6

Educating for resilience in the North: building a toolbox for teachers

¹Published manuscript: Spellman KV (2015) Educating for resilience in the North: building a toolbox for teachers. *Ecology and Society* 20(1):46. Special issue “Pathways of Resilience in a Rapidly Changing Alaska”

Abstract

Communities at far northern latitudes must respond rapidly to the many complex problems that are arising from a changing climate. An emerging body of theoretical and empirical work has explored the role that education plays in enhancing the resilience and adaptability of social-ecological systems. To foster effective, local and timely responses of high latitude communities to climate-driven social-ecological change, educators need access to successful and efficient teaching tools to foster resilience-promoting feedbacks. The potential for existing teaching practices to address this need, however, must be investigated and communicated to teachers. This paper reviews the education and sustainability science literature on attributes of resilience to which formal education can contribute and investigates teaching strategies that help enhance these attributes. Using examples from Alaska, I examine the potential for systems thinking, metacognition, scenarios thinking, citizen science, and stewardship learning to promote resilience in social-ecological systems. I begin to develop a toolbox of teaching strategies for resilience education and suggest policy for formal schools to incorporate these tools into everyday teaching practice.

Keywords: Alaska; citizen science; human capital, metacognition; pedagogy; scenarios thinking; sense of place; social capital; social-ecological resilience; systems thinking

Introduction

Learning is fundamental to social-ecological resilience (Folke et al. 2009), or the capacity to respond and shape change in ways that sustain and develop the fundamental function, structure, identity and feedbacks in a social-ecological system (Chapin et al. 2009). Only recently have education and social-ecological system resilience literature begun to address how the two fields might intersect and create learning opportunities that effectively target and contribute to resilience (Tidball and Krasny 2011). A growing body of research explores the way learning in informal education settings like youth camps, community groups, and urban gardens can build attributes of resilient social-ecological systems such as social capital, improved ecosystem services, and sense of place (Fazey et al 2007, Krasny and Tidball 2009a, Kofinas 2009, Tidball and Krasny 2010, Kudryavtsev et al. 2012a). Far less has been done investigating the strategies or teaching tools available to compulsory school teachers to help foster these resilience-building outcomes (but see Sriskandarajah et al. 2010). In a recent special issue of *Ecology and Society*, formal schooling attainment was linked in numerous studies to decreases in disaster vulnerability and enhanced resilience (reviewed in Muttarak and Lutz 2014). Formal school teachers around the globe comprise a large potential force to shape the ability of society to navigate the rapid changes that currently challenge us. Resilience researchers have called for radical transformations in the way society thinks and learns toward a more holistic, systematic, integrative, and participatory mode, but this transformation is unlikely to occur unaided (Sterling 2010). There is a clear need at the intersection of resilience and education research to identify, test, and refine teaching strategies that can best encourage and aide formal school teachers in building the capacities in their students necessary for managing rapid global changes.

There is perhaps no place where this need is more urgent than in high latitude northern systems, which are in the midst of unprecedented rates of social and ecological change (Hinzman

et al. 2005, Huntington et al. 2007). Increasing fire frequency, permafrost degradation, coastal erosion, spread of invasive species, decreasing sea ice extent, increasing human population, and accumulating human impacts on ecosystems, among other changes, interact to create challenges that arctic and subarctic communities must address to sustain themselves (ACIA 2004). In Alaska, public health, transportation, industry and public works are all being affected by the changing conditions (Markon et al. 2012). Environmental changes have also threatened many indigenous Alaskan villages, forcing migration of communities due to accelerated erosion, flooding or permafrost thaw (Maldonado et al. 2013). Changes in disturbance regimes and access have also disrupted traditional subsistence food practices (Kofinas et al. 2010). A rapidly changing climate has hastened many of these changes (ACIA 2004) and decreased the response time that northern communities have to tackle the complex problems that arise. Alaskan teachers could be a large systematic force and asset for helping create a society able to navigate rapid climate-driven change, and have heightened need to obtain teaching tools that most effectively and efficiently foster social-ecological resilience.

The objective of this manuscript is to identify and discuss teaching strategies for K-16 classroom teachers in Alaska, or beyond, that target specific attributes of social-ecological system resilience. In the first section, I review some of the attributes of resilient social-ecological systems that classroom teaching strategies could support. In the second section, I examine some of the learning tools that have both been proposed within the resilience literature to enhance the resilience of a social-ecological system, and been developed and tested within the education literature. I provide examples of implementing these learning tools in formal education settings, and where possible, in Alaska. I conclude with a discussion of potential hurdles and potential solutions for incorporating these tools into common teaching practice.

Resilience attributes and education

The sustainability of a system is often thought of as the long term maintenance of, or investment in, the capital within the system (Chapin et al. 2009). The forms of capital include natural, built, human and social capital (Arrow et al. 2004). The concept of capital has provided a way to quantify or assess whether a management decision or social practice is sustainable (Arrow et al. 2004). Multiple authors within the resilience literature have suggested that communities with higher levels of human and social capital not only can sustain themselves, but are better able to respond to and shape changes in the social-ecological system (i.e. more resilient; Ostrom 2000, Adger 2003, Walker and Salt 2006, Plummer and FitzGibbon 2007, Muttarak and Lutz 2014). In their conceptual framework on resilience and education, Tidball and Krasny (2010, 2011) identify social capital, particular aspects of human capital, and sense of place as key outcomes of education that generate resilience-supporting feedbacks within a social-ecological system. Human capital, social capital, and sense of place are constructs that span multiple disciplines, scales, and definitions (Kudryavtsev et al. 2012a, 2012b, Krasny et al. 2013). This section of the paper draws upon education and resilience research to discuss and defines these elements within the Tidball and Krasny (2010, 2011) framework.

Human capital

Human capital is defined as the skills and capabilities that enable a person to act in new ways in the education literature (Coleman 1988) or as the capacity of people to accomplish their goals in the resilience literature (Arrow et al. 2004). Both agree that human capital is increased by learning (Coleman 1988, Arrow et al. 2004). In fact, most social science studies on the subject use the level of education attained, or level of education attained by parents in the case of youth, as the primary indicator of human capital (reviewed in Ferguson 2006).

Both current trends in education policy and practice, and thinking within resilience theory call for a shift in investment in human capital from the more traditional investment in knowledge acquisition, to investment in critical and reflective thinking skills (Duschl et al. 2007, Fazey et al. 2007, Sterling 2010, NRC 2012). In their National Research Council education research review of best practices in science education, Duschl et al. (2007) advocated that the developers of mandated curricula and science education standards shift focus from science as a collection of facts to science as a reflective and iterative process. The USA national *Framework for K-12 Science Education* (NRC 2012) responds to this recommendation by emphasizing the crosscutting concepts and practices of science, such as systems modelling, stability, and change, throughout the newest national science standards (the *Next Generation Science Standards*). Human capital investments that have been advocated for in the resilience literature primarily include thinking skills that improve people's ability to anticipate, understand, reflect upon, and learn from change within a complex social-ecological system (Carpenter 2002, MEA 2005, Fazey et al. 2007, Ascher 2009, Chapin et al. 2009, Kofinas 2009, Tschakert and Dietrich 2010, Tidball & Krasny 2011). Understanding which teaching tools can best help teachers achieve this shift in human capital investment will clearly aide this effort. It can be argued that the goal of all education strategies is to increase human capital. This paper, therefore, identifies teaching strategies that increase the above mentioned specific aspects of human capital advocated for in the resilience literature and recent education reforms.

Social capital

Social capital is defined as relationships between people that facilitate action (Coleman 1988). In a formal education setting, this includes relationships between students, parents, educators and the broader community that promote learning (Coleman 1988). The concept of social capital has been used widely to help explain academic success in at-risk youth (Coleman

1988, Furstenburg and Hughes 1995, Dyk and Wilson 1999) and youth development outcomes (reviewed in Ferguson 2006). Coleman (1988) argues that investment in social capital within school systems is as important as the more traditional investment in human capital in determining the ability of students and communities to successfully learn and act in new ways. Within the resilience literature, Ahn and Ostrom (2008) go beyond the Coleman (1988) definition of social capital to include the values and relationships that have been created in the past that can be used to navigate social-ecological problems in the present or future.

In a systematic review of education studies using social capital as a guiding construct, Ferguson (2006) identifies community social capital as a major contributor to a child's well-being. Education, social science, and resilience researchers typically group indicators of community social capital into three categories: social support networks, civic engagement in local institutions, and trust and safety (Putnam 1995, Ferguson 2006, Ahn and Ostrom 2008). In their pioneering literature synthesis and pilot study, Krasny et al. (2013) developed a conceptual model that links social capital to attributes of social-ecological resilience that environmental education can stimulate, including positive youth development, community well-being, natural capital, and ecosystem services. Their pilot survey measuring social capital in inner-city youth found that students involved in community-based environmental stewardship projects showed increased informal socialization and diversity of friendships, two indicators of social support networks in youth, compared to students who did not participate in similar environmental education programs (Krasny et al. 2013). They propose that by continuing to engage students in these types of environmental stewardship projects, amplifying feedbacks for resilience can be created for a community at the interface of education and local resource management (Krasny et al. 2013).

Sense of place

Sense of place is the “meanings and attachment to a setting held by an individual or group” (Stedman 2002). This definition highlights the two major components of the sense of place construct: 1) place meaning, or the symbolic meanings that people assign to places, and 2) place attachment, or the bond between people and their environment (Stedman 2002). Sense of place has received increasing attention in the resilience literature as an attribute within individuals or groups of people that can foster social-ecological resilience (Kudryavtsev et al. 2012a, 2012b). Sense of place has also received prominent attention in child development and education literature as critical to youth well-being (Chawla 1992, Wilson 1997, Capra 1999, Louv 2008, Russell et al. 2013). Several empirical studies have demonstrated that the meanings and attachments people give to places can stimulate human capital by increasing pro-environmental behaviors, concerns, and intentions (Stedman 2002, Walker and Chapman 2003, Ryan 2005, Rioux 2011). Other empirical and theoretical studies suggest that the learning and knowledge about a place (existing human capital) can change the attachment and meaning they give to the place (Taun 1977, Semken et al. 2009). When strong sense of place is held by a group, several authors theorize that social capital can be increased by connecting people through a common concern and identity and increase the capacity for collective action to manage natural resources (Ostrom 1990, Miller 1992, Ahn and Ostrom 2008). Eisenhauer et al. (2000) found that social interactions can also be an important contributor to developing place attachment. These studies suggest that sense of place has a reciprocal relationship with human and social capital, with these stocks for resilience both contributing to sense of place and sense of place contributing to them. This amplifying feedback may promote resilience by increasing the capacity for and likelihood of individuals or communities actively managing changes in social-ecological systems.

Review of resilience learning tools

Specific teaching practices have been suggested in the resilience literature to help enhance human capital, social capital, or sense of place. These strategies include systems thinking (Sterling 2003, Kofinas 2009), metacognition (Fazey et al. 2007), scenarios thinking (MEA 2005, Kofinas 2009), citizen science (Berkes 2002, Jordan et al. 2012, Tidball and Krasny 2012) and stewardship learning (Kevany 2007, Krasny and Tidball 2009a, 2009b). I chose to discuss these five tools in the following section because all have been thoroughly researched within the education literature and have potential to be practically applied in formal classroom settings to target learning toward the above attributes of resilient social-ecological systems.

Systems thinking

Systems thinking is a mode of teaching that shifts the focus of learning beyond isolated facts and concepts to emphasize their relationships with other concepts in a systems context (Jordan et al. 2009, Boersma et al. 2011). Students are challenged to consider some of the fundamental properties of complex systems such as non-linear relationships (i.e. amplifying and stabilizing feedbacks) between system parts, system parts operating at multiple spatial or temporal scales, or emergent properties of systems that only occur when the multiple parts interact (Meadows 2008, Ben-Zvi Assaraf and Orion 2010). Jordan et al. (2009) propose that systems thinking can aid a student's construction of their own knowledge (cf. Driver et al. 1994). This is achieved by giving students practice developing mental models of abstract social-ecological concepts and fitting their new learning about a system within the constructs of their prior knowledge (Crawford and Jordan 2013).

Learners must be taught how to think in systems; systems thinking is not necessarily an innate skill (Sterman and Sweeney 2007). Students as young as 8 years old can gain systems thinking skills and apply them within a social-ecological context (Wylie et al. 1998), and these

sorts of learning interventions can have lasting effects (Ben-Zvi Assaraf and Orion 2010).

Placing learning within a social-ecological systems context may further enhance the impact this tool has on fostering resilience (Sterling 2003, Kyburz-Graber et al. 2006, Krasny 2009). The learning strategy has been employed in resource management planning workshops to help visualize the impacts of climate change on communities (Cone et al. 2012, Gray et al. 2012, Cone et al. 2013). Cone et al. (2012), for example, found that by using concept mapping to facilitate systems thinking, participants were better able to gauge the complex risks climate change might bring to their community, and better plan to reduce those risks. Within youth education settings, Crawford and Jordan (2013) advocate for greater use of systems thinking and practice with conceptual modelling in science and environmental education to build student capacity to think critically about our changing social-ecological systems.

In Alaska, systems thinking has taken a prominent role as a learning strategy in the Alaska Seas and Rivers Curriculum (Alaska Sea Grant 2009). The enduring understandings that the curriculum uses to frame the learning goals of the lessons include the following: “watersheds, rivers, wetlands, and the one big ocean of the world are an interconnected system,” “the ocean and humans are inextricably linked,” and “connections between humans and the ocean are important.” Several lessons include drawing or building models of local or global scale social-ecological systems. Table 6.1 contains practical methods that have been used in classrooms in places other than Alaska to apply systems thinking in formal education programs.

Metacognition

Both education and resilience scholars have argued that an increased emphasis on metacognition, or the knowledge of and ability to regulate one’s own thinking and learning, is essential to building adaptive capacity of individuals and societies (Bransford et al. 2000, Fazey et al. 2007). Metacognition is inherent in the concept of multiple loop learning, which combines

metacognition with group learning from actions and is commonly cited in adaptive management and resilience literature (Argyris and Schön 1978, Senge 1990, Kofinas 2009). A broad and diverse body of education literature has explored the impact of metacognition on learning (reviewed in Dignath and Buttner 2008) and many implementation strategies that have been developed for classroom use (see Table 6.1 for examples). Metacognitive ability can increase with age (Flavell et al. 1995) and with practice throughout our lives (Brown and DeLoache 1978, Doran and Cameron 1995). Compared to students who learned through other approaches, students who practiced metacognitive learning improved their level of discourse on ecological topics and showed longer term retention of their ecology understanding (Blank 2000). Further, students who practice metacognition showed greater fluid intelligence, the kind of knowledge that allows for problem solving when faced with new information or stimuli (Rosencwajg 2003). These empirical studies suggest that metacognitive teaching approaches may be useful in enhancing student ability to apply knowledge flexibly and restructure knowledge in the face of rapid environmental change.

A recent study in Alaska tested whether explicit metacognitive practice could improve environmental problem solving skills on a local rapid social-ecological change issue, non-native plant invasion in the boreal forest (Chapter 5). Half of the 108 seventh grade students had daily metacognitive practice embedded into their lessons in the form of metacognitive journaling exercises, while the other half of the students did not. Compared to students who did not complete daily metacognitive journaling, students with initially low problem solving ability who practiced metacognition tended to show greater improvement in their critical thinking skills on an environmental problem-solving assessment. This experiment demonstrates that explicit instruction in metacognition can increase the kinds of human capital thought to build resilience by creating better critical thinkers and social-ecological problem solvers.

Scenarios thinking

Effective planning and thinking about the future is a skill that can be taught (Ornauer et al. 1976, Hicks and Holden 1995, Liedtka 1998, Ascher 2009). Scenarios thinking is a tool that encourages learners to create multiple stories about possible futures based on a range of decisions in complex settings (Mietzner and Reger 2005). By imagining multiple possible paths for the future, individuals, communities, or societies can better understand their options, identify priorities for action, and plan for a positive future (Mietzner and Reger 2005, Carpenter et al. 2006). The learning tool is used in natural resource management, including in Alaska, to help communities faced with resource dilemmas choose paths that will best help them achieve desired management outcomes in the future (Chapin et al. 2003, Peterson et al. 2003, Carpenter et al. 2006, Ernst and van Riemsdijk 2013).

The explicit practice of scenarios thinking in educational settings could also enhance a person's willingness to engage in stewardship activities. Hicks and Holden (1995) found that when people imagine the future, they, more often than not, imagine local and global problems staying the same or getting worse than they are now. These pessimistic visions of the future can lead people to believe their present actions will not make a difference in the future, and provides them with little motivation for behavior changes (Hicks and Holden 1995). By incorporating scenarios thinking into learning experiences (examples in Table 6.1), educators could improve the forms of human capital that contributes to resilience by increasing people's skill-level at imagining a desirable future and believing that their actions can make a contribution toward achieving it (sensu Hicks and Holden 1995, Mietzner and Reger 2005). Further, by practicing scenarios thinking learners become better prepared to deal with uncertainty and surprises (Mietzner and Reger 2005).

Citizen science

Citizen science refers to partnerships between scientists and non-scientists to conduct authentic scientific research on a topic of interest or concern (Conrad and Hilchey 2011, Jordan et al. 2012). It includes a spectrum of learning experiences from “citizen as data collector” for scientists with a pre-defined questions or long-term monitoring goals, to “citizen as scientist” collecting and analyzing data on community-generated questions with the assistance of experts (Conrad and Hilchey 2011, Shirk et al. 2012). Citizen science can also take the form of community-scientist partnerships to document change through the collection of local and traditional ecological knowledge (Bäckstrand 2003). The usefulness of citizen science as both an ecological methodology and a learning tool has received rapidly increasing attention in the peer-reviewed literature over the past two decades (Silvertown 2009, Bonney et al. 2014).

Many of the documented outcomes of citizen science programs show potential for gradual shifts in the way both scientists and community members think, their skills for solving social-ecological problems, and what they value (Turnbull et al. 2000, Brossard et al 2005, Jordan et al. 2011, Dickinson et al. 2012, Jordan et al. 2012). Through collaborative action and dialogue, citizen science has also been suggested as a tool to build elements of social capital such as social networks and trust between scientists, land managers and a diverse public (Bäckstrand 2003, Jordan et al. 2012, Pandya 2012). Berkes (2002) suggests that citizen science can be used as an important strategy to create cross-scale linkages in resource management. Citizen science gives local stakeholders the opportunity to contribute to the scientific knowledge that informs the resource management policies being created at regional or national scales (Berkes 2002). Building on this idea, Tidball and Krasny (2012) used examples of citizen science in post-disaster cases to demonstrate how the learning tool can be used in adaptive co-management. As suggested by Berkes (2002), Tidball and Krasny (2012) argued that citizen science can help

tighten the feedback loops between stakeholders and management actions and build resilience in a social-ecological system.

Citizen science has also been associated with a deepened sense of place (Evans et al. 2005). Evans et al. (2005) analyzed outcomes from a backyard bird ecology citizen science program using interviews and surveys and found increases in participants' sense of place. They define sense of place as the knowledge and awareness of and willingness to care for a certain place (Evans et al. 2005). This definition falls more within the place attachment side of the sense of place construct defined by Stedman (2002) than within the place meaning aspect of the construct. Feeling more connected and aware of the events in their backyards after spending time collecting data, long-time residents started noticing and identifying different bird calls. In addition, more than half the participants had changed a stewardship behavior in relationship to their yard (Evans et al. 2005).

One citizen science program in Alaska, the Melibee Project, teams volunteers from across Alaska with ecologists at the University of Alaska to address the potential for competition between native berry plants (*Vaccinium* spp.) and an invasive plant (*Melilotus albus*) for pollinators (Chapter 4). Trained volunteers track the flowering phenology the focal species throughout the growing season. Compared to before they participated in the project, Melibee Project volunteers increased their scientific knowledge and process skills through volunteer trainings and teacher workshops (Appendix A). They reported increases in their awareness of invasive plants, awareness of the phenological events around them, and frequency of engaging in stewardship activities such as pulling invasive plants, participating in community weed removal events, or reporting suspicious plants to experts (Appendix A). In addition to these human capital increases, the Melibee Project facilitated collaboration and networking among K-16 students,

teachers, other volunteers, scientists, land managers and tribal leaders for science-based resource management (Bestelmeyer et al. 2015).

Stewardship learning

Stewardship learning is a strategy where learners make an active contribution to improving their environment while learning about the processes and issues that they are working towards bettering (Cramer 2008). It necessitates drawing students into community life and engaging them in their ecological setting (Kevany 2007). Stewardship learning can often lead to improvements in ecosystem structure and functioning, and builds skills and values such as planning ability, scientific knowledge, sense of place, and understanding of social-ecological systems (Krasny and Tidball 2009b, Tidball and Krasny 2010). For example, the stewardship learning in the Cornell Civic Ecology Lab's urban gardening program provided participants with skills essential to the adaptive co-management process, such as learning as a group through experience, experimentation, and innovation (Krasny and Tidball 2009b). In another study comparing students who participated in environmental and non-environmental youth programs in New York City, Kudryavtsev et al. (2012a) found that students engaged in environmental stewardship developed stronger place attachments and place meanings than the students in non-environmental programs. They propose that educational programs that engage students in meaningful stewardship activities within their own communities can be a source of important resilience building feedbacks that immediately improves ecosystems and builds the sense of place necessary to sustain them (Kudryavtsev et al. 2012a). Similar social and ecological benefits have been documented in myriad other studies on the impacts of stewardship learning (reviewed in Billig 2000).

The Center for Alaskan Coastal Studies, an environmental education non-profit in Homer, Alaska, has been running a stewardship learning program called Kachemak CoastWalk

since 1984 (CACS 2014). Every September, around 600 volunteers, including several hundred K-16 students and teachers, remove marine debris and conduct biodiversity and human impact surveys of adopted beach zones (CACS 2014). The program gives students an opportunity to learn about marine debris and coastal change through an in-classroom curriculum (Trowbridge et al. 2004), and immerses them in large-scale community action on these issues. Changes in participant sense of place, particularly place attachment, have been documented anecdotally as a result of the stewardship project (Sigman and Trowbridge 2004), and the community art program that has become a part of the annual effort has allowed local artists to visually express the place meanings that they have developed using the marine debris they remove from their beach (CACS 2014).

Institutional hurdles and policy suggestions

The manner in which human and social capital assets are built and used depends largely upon the institutions that guide these forms of capital (Arrow et al. 2004). In this final section, I discuss curriculum policy, evaluation and teacher training as aspects of educational institutions that present both potential hurdles and avenues for facilitating the incorporation of the learning tools discussed above into regular classroom teaching practice.

Resilience learning tools in compulsory curriculum

Mandated curriculum at local, state, and national scales provides a structure for new trends and best practices in education to be broadly disseminated and applied. Within compulsory public education systems, mandated curriculum could help the resilience-building learning tools discussed here reach a high proportion of the school-aged population. Curriculum policies that promote concepts of sustainability and resilience have been mandated in some national education agendas (Examples: futures thinking in New Zealand and Australia (Jones et al. 2011), sustainability concepts in France (Simonneaux and Simonneaux 2011). The resilience

framework for education proposed by Tidball and Krasny (2010, 2011) may serve as an important tool for curriculum developers and teachers seeking to align curriculum learning goals with resilience-based outcomes.

Evaluation of learning within a resilience framework

In their study of the integration of environmental education into local curriculums in Taiwan, Yueh et al. (2010) found that the more holistic and action-oriented student learning outcomes were more difficult to measure than in traditional school subjects because they are hard to capture with the available assessment tools like written tests. If the shift toward greater state mandated emphasis on process skills in curriculum continues (for example NRC 2012), learning tools that support resilience may be increasingly practical for educators to use and evaluate. Learning progressions, models for student learning that take concepts or skills through increasing levels of complexity and sophistication (Duschl et al. 2011), could potentially be used to structure, guide, and measure student progress in resilience thinking skills, and to construct curricula with resilience-based learning outcomes (cf. Ben-Zvi Assaraf and Orion 2005, Lee and Lui 2010, Robertson et al. 2012).

Teacher training to support resilience learning

A major institutional hurdle that must be overcome to ensure learning for resilience within schools is the lack of teacher training in the pedagogies discussed in this paper. For example, many teachers lack the skills and knowledge to teach systems thinking or integrated social-ecological systems (Stermann and Sweeney 2007, Almeida and Vasconcelos 2011). In Alaska, one of the first steps toward creating a society that has the capability to respond and adapt to rapid change should be to provide professional development workshops and core course work for current and prospective teachers on the thinking skills and learning tools discussed in this paper.

Conclusions

Education and resilience theorists have called for further investigation of the role education can play to sustain social-ecological systems in the face of a changing climate (Fazey et al. 2007, Krasny et al. 2009, Krasny and Tidball 2009a, Tidball and Krasny 2010, Tidball and Krasny 2011). In response to this call, this paper investigated attributes of resilient social-ecological systems to which formal education can contribute and presents the beginning of a resilience teaching toolbox for K-16 educators. The resilience learning tools this paper suggests are clearly insufficient in and of themselves to meet the needs of the scale and rate of climate change in Alaska, or elsewhere. However, this paper presents an initial step toward thinking about practical applications for resilience theory in classrooms. Future research on pedagogies that can best build resilience is needed, particularly within the arctic and subarctic communities undergoing the most rapid change. Formal school teachers can play an enormous role in facilitating the transformations in the way society thinks and learns that resilience requires (e.g. Sterling 2010), and the intersection between education and resilience research is ripe for the picking to aid them in this profound task.

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Literature cited

- ACIA. 2004. Impacts of a warming climate: Arctic Climate Impact Assessment. Cambridge University Press. Cambridge, UK.
- Adger, W. N. 2003. Social capital, collective action, and adaptation to climate change. *Economic Geography* 79 (4): 387–404.
- Argyris, C. and D. Schön. 1978. Organizational learning: a theory of action perspective. Addison-Wesley, Reading, MA.
- Almeida, A., and C. Vasconcelos. 2011. Teachers' perspectives on the human-nature relationship: implications for environmental education. *Research in Science Education*. DOI 10.1007/s11165-011-9272-z
- Ahn, T. K., and E. Ostrom. 2008. Social capital and collective action. Pgs. 70-100 in D. Castiglione, J.W. van Deth, and G. Wolleb (eds) *The Handbook of Social Capital*. Oxford University Press, Oxford, UK.
- Alaska Sea Grant. 2009. Alaska Seas and Rivers Curriculum, Alaska Sea Grant, Anchorage, Alaska. [online] URL: <http://seagrant.uaf.edu/marine-ed/curriculum/>
- Arrow, K., P. Dasgupta, L. Goulder, G. Daily, P. Ehrlich, G. Heal, S. Levin, K. Mäler, S. Schneider, D. Starrett, B. Walker. 2004. Are We Consuming Too Much? *The Journal of Economic Perspectives* 18: 147-172.
- Ascher, W. 2009. Bringing in the Future: Strategies for Farsightedness and Sustainability in Developing Countries. University of Chicago Press. Chicago , USA.
- Bäckstrand, K. 2003. Civic science for sustainability: reframing the role of experts, policy-makers and citizens in environmental governance. *Global Environmental Politics* 3(4):24- 41.

- Ben-Zvi Assaraf, O., and N. Orion. 2005. Development of system thinking skills in the context of earth systems education. *Journal of Research in Science Teaching* 42:518–560.
- Ben-Zvi Assaraf, O., and N. Orion. 2010. Four case studies, six years later: developing system thinking skills in junior high school and sustaining them over time. *Journal of Research in Science Teaching* 47: 1253-1280.
- Berkes, F. 2002. Cross-scale institutional linkages: perspectives from the bottom up. Pages 293-321 in E. Ostrom, T. Diez, N. Dolsak, P.C. Stern, S. Stovich, et al. (Eds.) *The Drama of the Commons*. National Academy Press, Washington D.C.
- Bestelmeyer, S., M. M. Elser, K.V. Spellman, E. B. Sparrow, S. Haan-Amato, and A. Keener. 2015. Collaboration, interdisciplinary thinking, and communication: applying shifting paradigms in ecology for K-12 education. *Frontiers in Ecology and the Environment* 13: 37–43.
- Billig, S. H. 2000. Research on K-12 school-based service-learning: the evidence builds. *Phi Delta Kappan* 81: 658-664.
- Blank, L.M., 2000. A metacognitive learning cycle: a better warranty for student understanding? *Science Education* 84: 486-506.
- Boersma, K., J. Arend, and K. Klaassen. 2011. The feasibility of systems thinking in biology education. *Journal of Biological Education* 45:190-197.
- Bonney, R., J. L. Shirk, T. B. Phillips, A. Wiggins, H. L. Ballard, A. J. Miller-Rushing, and J. K. Parrish. 2014. Next steps for citizen science. *Science* 343:1436-1437.
- Bransford, J. D., A. L. Brown, and R. R. Cocking. 2000. How people learn: brain, mind, experience, and school. National Academy Press, Washington, D.C.

- Brossard, D., B. Lewenstein, and R. Bonney. 2005. Scientific knowledge and attitude change: The impact of a citizen science project. *International Journal of Science Education* 27 (9):1099–1121.
- Brown, A. L., and J. S. DeLoache. 1978. Skills, plans, and self-regulation. In R.S. Siegler (Ed) *Children's thinking: what develops?* Lawrence Erlbaum, Hillsdale, New Jersey, USA.
- CACS- Center for Alaskan Coastal Studies. 2014. Kachemak Bay CoastWalk. Center for Alaskan Coastal Studies website. Homer, Alaska. [online] URL: <http://www.akcoastalstudies.org/outreach/international-coastal-cleanup/kachemak-bay-coastwalk.html>
- Capra F. 1999. Ecoliteracy: The Challenge for Education in the Next Century. Center for Ecoliteracy, Berkeley, CA.
- Carpenter, S. R. 2002. Ecological futures: building an ecology of the long now. *Ecology* 83:2069–2083.
- Carpenter, S. R., E. M. Bennett, and G. D. Peterson. 2006. Scenarios for ecosystem services: an overview. *Ecology and Society* 11(1): 29.
- Chapin, F. S. III, G. P. Kofinas, and C. Folke (eds). 2009. Principles of ecosystem stewardship: Resilience-based resource management in a changing world. Springer, New York, NY.
- Chapin, F. S. III, T. S. Rupp, A. M. Starfield, L. DeWilde, E. S. Zavaleta, N. Fresco, J. Henkelman, and A.D. McGuire. 2003. Planning for resilience: modeling change in human–fire interactions in the Alaskan boreal forest. *Frontiers in Ecology and the Environment* 1(5): 255–261.
- Chawla, L. 1992. Childhood place attachments. Pgs. 63–86 in *Place Attachment*, Vol. 12, ed. I. Altman and S.M. Low, Plenum Press, New York, NY.

- Coleman, J. 1988. Social capital in the creation of human capital. *American Journal of Sociology* 94:95–120.
- Cone, J., S. Rowe, J. Borberg, and B. Goodwin. 2012. Community planning for climate change: visible thinking tools facilitate shared understanding. *Journal of Community Engagement and Scholarship* 5:5-17.
- Cone, J., S. Rowe, J. Borberg, E. Stancioff, B. Doore, and Kristen Grant. 2013. Reframing engagement methods for climate change adaptation. *Coastal Management* 41: 345-360.
- Conrad, C. C., and K. G. Hilchey. 2011. A review of citizen science and community-based environmental monitoring: issues and opportunities. *Environmental Monitoring and Assessment* 176:273–291.
- Cramer, J. R. 2008. Reviving the connection between children and nature through service learning restoration partnerships. *Native Plants* 9:278-286.
- Crawford, B.A., and R. Jordan. 2013. Inquiry, models, and complex reasoning to transform learning in environmental education. Pages 105- 123 *In* M. E. Krasny and J. Dillon (eds). *Trading Zones in Environmental Education: Creating Transdisciplinary Dialogue*. Peter-Lang, New York City, NY.
- Dickinson, J. L., J. Shirk, D. Bonter, R. Bonney, R. L. Crain, J. Martin, T. Phillips, and K. Purcell. 2012. The current state of citizen science as a tool for ecological research and public engagement. *Frontiers in Ecology and the Environment* 10: 291–297.
- Dignath, C., and G. Buttner. 2008. Components of fostering self-regulated learning among students. A meta-analysis on intervention studies at primary and secondary school level. *Metacognition Learning* 3:231-264.
- Doran, C., and R. J. Cameron. 1995. Learning about learning. *Educational Psychology in Practice* 11:15–23.

- Driver, R., H. Asoko, J. Leach, E. Mortimer, and P. Scott. 1994. Constructing scientific knowledge in the classroom. *Educational Researcher* 23: 5-12.
- Duschl, R., H.A. Schweingruber, and A. Shouse. 2007. Taking science to school: learning and teaching science in grades K-8. National Academy Press, Washington, DC.
- Duschl, R., S. Maeng, and A. Sezen. 2011. Learning progressions and teaching sequences: a review and analysis. *Studies in Science Education* 47: 123–182.
- Dyk, P. H., and S.M. Wilson. 1999. Family-based social capital considerations as predictors of attainments among Appalachian youth. *Sociological Inquiry* 69:477-503.
- Eisenhauer, B.W., R.S. Krannich, and D.J. Blahna. 2000. Attachment to special places on public lands: An analysis of activities, reasons for attachments, and community connections. *Society and Natural Resources* 13: 421–41.
- Ernst, K. M., and M. van Riemsdijk. 2013. Climate change scenario planning in Alaska's National Parks: Stakeholder involvement in the decision-making process. *Applied Geography* 45:22-28.
- Evans, C., E. Abrams, R. Reitsma, et al. 2005. The Neighborhood Nestwatch Program: participant outcomes of a citizen-science ecological research project. *Conservation Biology* 19: 589–94.
- Fazey, I., J. A. Fazey, J. Fischer, K. Sherren, J. Warren, R. F. Noss, and S. R. Dovers. 2007. Adaptive capacity and learning to learn as leverage for social-ecological resilience. *Frontiers in Ecology and the Environment* 5: 375-380.
- Flavell, J. H., F. L. Green and E. R. Flavell. 1995. Young children's knowledge about thinking. *Monographs of the Society for Research in Child Development* 60: 1–95.

- Folke, C., F. S. Chapin III and P. Olsson. 2009. Transformations in ecosystem stewardship. In F.S. Chapin III, G.P. Kofinas, and C. Folke (eds). *Principles of ecosystem stewardship: Resilience-based resource management in a changing world*. Springer, New York, NY.
- Ferguson, K. M. 2006. Social capital and children's wellbeing: a critical synthesis of the international social capital literature. *International Journal of Social Welfare* 15: 2–18.
- Furstenburg, F., and M. E. Hughes. 1995. Social capital and successful development among at-risk youth. *Journal of Marriage and the Family* 57:330-392.
- Gray, S., A. Chan, D. Clark and R.C. Jordan. 2012. Integrating stakeholder knowledge in social-ecological system decision-making: Benefits and limitations to knowledge diversity. *Ecological Modeling* 229: 88-96.
- Hennessey, M. 1991. Analysis of conceptual change and status change in sixth graders' concepts of force and motion. Doctoral dissertation, University of Wisconsin, Madison, WI.
- Hicks, D., and C. Holden. 1995. Exploring the future: a missing dimension in environmental education. *Environmental Education Research* 1:185-194.
- Hinzman, L. D., N. D. Bettez, W. R. Bolton, F. S. Chapin III, M. B. Dyurgerov, C. L. Fastie, B. Griffith, et al. 2005. Evidence and implications of recent climate change in northern Alaska and other arctic regions. *Climatic Change* 72:251–298.
- Hung, W. 2008. Enhancing systems-thinking skills with modeling. *British Journal of Educational Technology* 39: 1099-1120.
- Huntington, H. P., L. C. Hamilton, C. Nicolson, R. Brunner, A. Lynch, A. E. J. Ogilvie, and A. Voinov. 2007. Toward understanding the human dimensions of the rapidly changing arctic system: insights and approaches from five HARC projects. *Regional Environ Change* 7:173–186.

- Jones, A., C. Buntting, R. Hipkins, A. McKim, L. Conner, and K. Saunders. 2011. Developing students' futures thinking in science education. *Research in Science Education* DOI 10.1007/s11165-011-9214-9.
- Jordan, R.C., H. L. Ballard, and T. B. Phillips. 2012. Key issues and new approaches for evaluating citizen science learning outcomes. *Frontiers in Ecology and the Environment* 10: 307–309.
- Jordan, R.C., S. A. Gray, M. Demeter, L. Lui, and C. Hmelo-Silver. 2009. Systems and cycles teaching ecology. *Applied Environmental Education & Communication* 8:40-48.
- Jordan, R. C., S. A. Gray, D. V. Howe, W. R. Brooks, and J. G. Ehrenfeld. 2011. Knowledge gain and behavioral change in citizen-science programs. *Conservation Biology* 25:1148-1154.
- Kevany, K. D. 2007. Building the requisite capacity for stewardship and sustainable development. *International Journal of Sustainability in Higher Education* 8: 107-122.
- Kofinas, G. P. 2009. Adaptive co-management in social-ecological governance. In F.S. Chapin III, G.P. Kofinas, and C. Folke (eds). *Principles of ecosystem stewardship: Resilience-based resource management in a changing world*. Springer, New York, NY.
- Kofinas, G. P., F. S. Chapin, S. BurnSilver, J. I. Schmidt, N. L. Fresco, K. Kielland, S. Martin, A. Springsteen, and T. S. Rupp. 2010. Resilience of Athabascan subsistence systems to interior Alaska's changing climate. *Canadian Journal of Forest Research* 40:1347–1359.
- Krasny, M. E. 2009. A response to Scott's concerns about the relevance of environmental education research: applying social–ecological systems thinking and consilience to defining research goals. *Environmental Education Research* 15:189–198.

- Krasny, M. E., L. Kalbacker, R. C. Stedman and A. Russ. 2013. Measuring social capital among youth: applications in environmental education. *Environmental Education Research*, DOI: 10.1080/13504622.2013.843647
- Krasny, M. E., and K. G. Tidball. 2009a. Applying a resilience systems framework to urban environmental education. *Environmental Education Research* 15: 465–482.
- Krasny, M. E., and K. G. Tidball. 2009b. Community gardens as context for science, stewardship and advocacy learning. *Cities and the Environment* 2(1):article 8, 18 pp.
- Krasny, M. E., K. G. Tidball, and N. Sriskandarajah. 2009. Education and resilience: social and situated learning among university and secondary students. *Ecology and Society* 14(2): 38.
- Kudryavtsev, A., M.E. Krasny, and R. Stedman. 2012a. The impact of environmental education on sense of place among urban youth. *Ecosphere* 3(4): 29.
- Kudryavtsev, A., R. Stedman, and M. Krasny. 2012b. Sense of place in environmental education. *Environmental Education Research* 18: 229-50.
- Kyburz-Graber, R., K. Hofer, and B. Wolfensberger. 2006. Studies on a socio-ecological approach to environmental education: a contribution to a critical position in the education for sustainable development discourse. *Environmental Education Research* 12:101–114.
- Lee, H., and O. L. Liu. 2010. Assessing learning progression of energy concepts across middle school grades: The knowledge integration perspective. *Science Education* 94: 665–688.
- Liedtka, J. M. 1998. Strategic thinking: can it be taught? *Long Range Planning* 31:120-129.
- Louv, R. 2008. Last child in the woods: saving our children from nature-deficit disorder. Algonquin Press, Chapel Hill, NC.

- Maldonado, J. K., C. Shearer, R. Bronen, K. Peterson and H. Lazrus. 2013. The impact of climate change on tribal communities in the US: displacement, relocation, and human rights. *Climatic Change* 120:601–614.
- Markon, C.J., S.F. Trainor, and F.S. Chapin III. 2012. The United States National Climate Assessment: Alaska Technical Regional Report. U. S. Geological Survey, Circular 1379.
- MEA (Millenium Ecosystem Assessment). 2005. Ecosystems and Human Well-being: Scenarios. Island Press, Washington D.C.
- Meadows, D. 2008. Thinking in Systems: A Primer. Chelsea Green Publishing. White River Junction, Vermont, USA.
- Mietzner, D., and G. Reger. 2005. Advantages and disadvantages of scenario approaches for strategic foresight. *International Journal of Technology Intelligence and Planning* 1:220-239.
- Miller, B. 1992. Collective action and rational choice: Place, community and the limits to individual self-interest. *Economic Geography* 68:22-42.
- Muttarak, R. and W. Lutz. 2014. Is education a key to reducing vulnerability to natural disasters and hence unavoidable climate change? *Ecology and Society* 19(1): 42.
- NRC- National Research Council. 2012. A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas. Committee on a Conceptual Framework for New K-12 Science Education Standards. Board on Science Education, Division of Behavioral and Social Sciences and Education. The National Academies Press, Washington, DC.
- Ornauer, H., H. Wiberg, A. Sicinski and J. Galtung (Eds).1976. Images of the World in the Year 2000. Humanities Press, Atlantic Highlands, NJ, USA.
- Ostrom, E. 1990. Governing the commons. Cambridge University Press, New York, NY.

- Ostrom, E. 2000. Social capital: a fad or a fundamental concept? Pgs 172-214 In P. Dasgupta and I. Seragilden (eds) *Social Capital: A Multifaceted Perspective*. World Bank, Washington DC.
- Pandya, R. E. 2012. A framework for engaging diverse communities in citizen science in the US. *Frontiers in Ecology and the Environment* 10: 314–317.
- Peterson, G. D., T. D. Beard Jr., B. E. Beisner, E. M. Bennett, S. R. Carpenter, G. S. Cumming, C. L. Dent, and T. D. Havlicek. 2003. Assessing future ecosystem services: a case study of the Northern Highlands Lake District, Wisconsin. *Conservation Ecology* 7(3): 1. [online] URL: <http://www.consecol.org/vol7/iss3/art1>
- Plummer, R., and J. FitzGibbon. 2007. Connecting adaptive co-management, social learning, and social capital through theory and practice. Pgs 38-61 in D. Armitage, F. Berkes, and N. Doubleday, *Adaptive co-Management: Collaboration, Learning, and Multi-level Governance*. UBC Press, Vancouver, Canada.
- Putnam, Robert B. 1995. Bowling alone: America's declining social capital. *Journal of Democracy* 6 (1): 65–78.
- Riess, W., and C. Mischo. 2010. Promoting systems thinking through biology lessons. *International Journal of Science Education* 32: 705-725.
- Robertson, G. P., S. L. Collins, D. R. Foster, N. Brokaw, H. W. Ducklow, T. L. Gragson, C. Gries, S. K. Hamiltom, A. D. McGuire, J. C. Moore, E. H. Stanley, R. G. Waide and M. W. Williams. 2012. Long-term ecological research in a human-dominated world. *BioScience* 64:342-353.
- Rioux, L. 2011. Promoting pro-environmental behaviour: collection of used batteries by secondary school pupil. *Environmental Education Research* 17: 353–73.

- Rosencwajg, P. 2003. Metacognitive factors in scientific problem-solving strategies. *European Journal of Psychology of Education* 18: 281-294.
- Russell, R., A. D. Guerrey, P. Balvanera, R. K. Gould, X. Basurto, K.M.A. Chan, S. Klain, J. Levine, and J. Tam. 2013. Humans and nature: how knowing and experiencing nature affect well-being. *Annual Review of Environment and Resources* 38:473–502.
- Ryan, R.L. 2005. Exploring the effects of environmental experience on attachment to urban natural areas. *Environment and Behavior* 37: 3–42.
- Senge, P. M. 1990. The fifth discipline: the art and practice of the learning organization. Doubleday Currency Press, New York, New York.
- Semken, S., C. Butler Freeman, N. Bueno Watts, J.J. Neakrase, and R. Escobar Dial. 2009. Factors that influence sense of place as a learning outcome and assessment measure of place-based geoscience teaching. *Electronic Journal of Science Education* 13(2). [online] <http://ejse.southwestern.edu/article/view/7803>
- Shirk, J. L., H. L. Ballard, C. C. Wilderman, T. Phillips, A. Wiggins, R. Jordan, E. McCallie, M. Minarchek, B. V. Lewenstein, M. E. Krasny, and R. Bonney. 2012. Public participation in scientific research: a framework for deliberate design. *Ecology and Society* 17(2): 29.
- Sriskandarajah, N., R. Bawden, C. Blackmore, K. G. Tidball, and A. E. J. Wals. 2010. Resilience in learning systems: case studies in university education. *Environmental Education Research* 16:559–573.
- Sigman, M. and B. Trowbridge. 2004. CoastWalk 20th Anniversary Newsletter. Center for Alaskan Coastal Studies, Homer, AK. <http://www.akcoastalstudies.org/coastal-monitoring/kachemak-bay-coastwalk.html>
- Silvertown, J. 2009. A new dawn for citizen science. *Trends in Ecology and Evolution* 24:467-471.

- Simonneaux, J., and L. Simonneaux. 2011. Educational configurations for teaching environmental socioscientific issues within the perspective of sustainability. *Research in Science Education*. DOI: 10.1007/s11165-011-9257-y.
- Stedman, R.C., 2002. Toward a social psychology of place: predicting behavior from place-based cognitions, attitude, and identity. *Environment and Behavior* 34: 405–425.
- Sterling, S. 2003. Whole systems thinking as a basis for paradigm change in education: explorations in the context of sustainability. PhD Dissertation. University of Bath, Bath, England.
- Sterling, S. 2010. Learning for resilience, or the resilient learner? Towards a necessary reconciliation in a paradigm of sustainable education. *Environmental Education Research* 16:511-528.
- Sterman, J., and L. B. Sweeney. 2007. Understanding public complacency about climate change: adults' mental models of climate change violate conservation of matter. *Climatic Change* 80: 213-238.
- Thomas, G. P., and C. J. McRobbie. 2001. Using a metaphor for learning to improve students' metacognition in the chemistry classroom. *Journal of Research in Science Teaching* 38:222-259.
- Tidball K. G. and M. E. Krasny. 2010. Urban environmental education from a social-ecological perspective: conceptual framework for civic ecology education. *Cities and the Environment* 3(1):11.
- Tidball K. G. and M. E. Krasny. 2011. Toward an ecology of environmental education and learning. *Ecosphere* 2(2): 21.

- Tidball K. G. and M. E. Krasny. 2012. A role for citizen science in disaster and conflict recovery and resilience. Pg. 226-234 in J. L. Dickinson and R. Bonney. Citizen science: public participation in environmental research. Cornell University Press, Ithaca, NY.
- Trowbridge, B., M. Sigman, B. Murphy, L. Villarreal, and K. Mangin. 2004. Gulf of Alaska CoastWatch curriculum guide. Center for Alaskan Coastal Studies, Homer, Alaska.
- Tschakert, P., and K. A. Dietrich. 2010. Anticipatory learning for climate change adaptation and resilience *Ecology and Society* 15(2):11.
- Turnbull, D. J., R. Bonney, D. Bascom, and A. Cabral. 2000. Thinking scientifically during participation in a citizen science project. *Science Education* 84:265–275.
- Walker, G. J., and R. Chapman. 2003. Thinking like a park: the effects of sense of place, perspective taking, and empathy on pro-environmental intentions. *Journal of Park and Recreation Administration* 21:71–86.
- Walker, B. H., and D. Salt. 2006. Resilience Thinking: Sustaining Ecosystems and People in a Changing World. Island Press, Washington, DC.
- Wall, K., S. Higgins, and L. Tiplay. 2009. Pupil views templates: exploring pupils perspectives of their thinking about learning. 1st International Visual Methods Conference, Leeds, UK.
- Wilson, R. 1997. A sense of place. *Early Childhood Education Journal* 24: 191–194.
- Wylie, J., N. Sheehy, C. McGuinness, and G. Orchard. 1998. Children's thinking about air pollution: a systems theory analysis. *Environmental Education Research* 4: 117-137.
- Yueh, M. M., B. Cowie, M. Barker, and A. Jones. 2010 What influences the emergence of a new subject in schools? The case of environmental education. *International Journal of Environmental and Science Education* 5:265-285.

Table 6.1 Toolbox of some practical implementation strategies for resilience learning tools in K-16 classrooms, including systems thinking, metacognition, and scenarios thinking.

Learning Tool	Implementation Strategy	How it works...
Systems Thinking	Systems drawings	Students draw illustrations of the different system components showing relationships and processes within the system (Ben-Zvi Assaraf and Orion 2005).
	Concept maps	Students are given a set of words representing system components and processes. Students arrange the words in a diagram and illustrate connections between the words to show their relationships (Ben-Zvi Assaraf and Orion 2005).
	Computer-based modeling	Students conceptualize a system in a user-friendly modelling interface and convert the relationships (including non-linear relationships and feedbacks) into numerical formulas (Hung 2008, Riess and Mischo 2010).
Metacognition	Metacognitive journaling	Students reflect on their learning by checking the development or status of their ideas. Students make sense of their idea, place it in the constructs of their prior knowledge, and reflect on the fruitfulness of the idea (i.e. does the idea help solve problems or encourage other ideas; Hennessey 1991, Blank 2000).
	Metacognitive illustration	Students draw illustrations of themselves and what they are thinking in relation to different learning tasks (Wall et al. 2009).
	Constructivist metaphor	Classroom dialogue periodically referenced the phrase “Learning is constructing” during learning activities (Thomas and McRobbie 2001).
Scenarios Thinking	Backward and forward timeline creation	Students place a desired future at the end of a timeline and construct the events that could lead from the desired state back to the present, or vice versa, starting at the present and creating a timeline of decisions that lead to variety of unknown futures (Jones et al. 2011).
	Futures wheels	Students use concentric wheels to visualize the effects of events, with a future event placed in the middle, direct effects of that event in a ring around the future event, and indirect effects in succeeding rings (Jones et al. 2011).
	Cross impact matrices	Students assess positive or negative interactions between possible future events by writing events horizontally and vertically along a grid (Jones et al. 2011).

CHAPTER 7

Conclusion

**Managing berries and invasive plants in Alaska: insights from ecology and
education research**

The ecological research goal of my dissertation was to investigate the impact of non-native plant invasions on the pollination and reproduction of native plants. The education research goal of this dissertation was to investigate the role two different education strategies, citizen science and metacognitive learning, can play in building resilience to non-native plant invasions in Alaska. Perspectives from both disciplines contribute to the larger goal of sustaining subsistence berry resources in the face of accelerating non-native plant invasions in Alaska.

Often education and outreach are considered peripheral activities to a scientific research program (Burggren 2009; Pace et al. 2010). For example, as of 2009, only 37 % of the broader impact statements in funded NSF projects proposed communicating research results or offering educational experiences to non-academic communities (Roberts 2009). These proposed education and outreach activities tended to not be well woven into the fabric of the proposal, and the principal investigators who proposed them tended not to be well qualified to effectively execute the activity (Burggren 2009). In Alaska's approach to invasive plant species (see Graziano 2011), there is a similar need to better integrate education and outreach activities, education research, and personnel with education expertise into the current strategy for research and management. My dissertation suggests that both ecological research and education research can contribute to a better understanding of how to manage natural resources. To conclude my dissertation, I summarize and synthesize the insights each chapter provides using the integrated social-ecological systems framework for my study system (Fig. 7.1, linkages A-D).

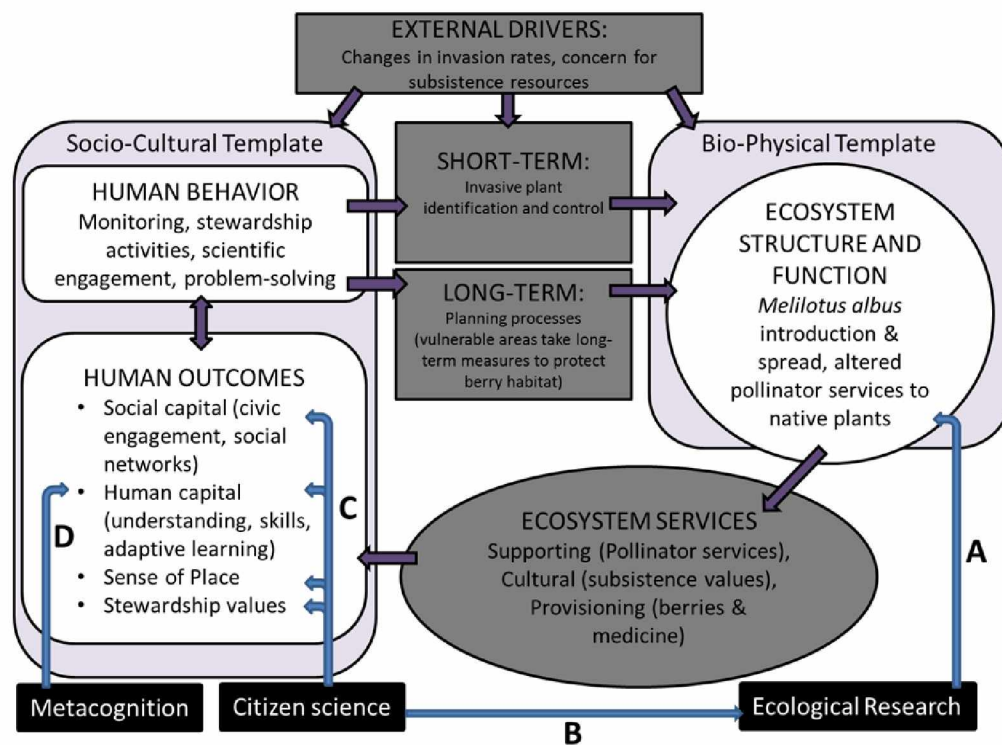


Figure 7.1 Revisited conceptual framework defining the integrated dissertation study system. The contribution that each major dissertation component (ecological research, citizen science, and metacognition experiment) offers to the understanding of the system is indicated by linkages A-D. Framework adapted from Tidball and Krasny (2010) and Collins et al. (2011).

Linkage A- Ecological field experiments and understanding the effects of sweetclover on pollination

Contrary to the majority of published studies on the effects of invasive plants on pollination of native plants (e.g. Grabas and Lavery 1999, Chittka and Schürkens 2001, Brown et al. 2002, Moragues and Traveset 2005, Totland et al. 2006; Traveset and Richardson 2006), *Melilotus albus* did not have a strong competitive effect on the native species we studied (Chapter 2). *M. albus* facilitated greater seed production per berry in *V. vitis-idaea* when we added large patches, and had a weak competitive effect on *R. groenlandicum* pollination, but did not change fruit or seed production. *M. albus* had no detectable effect on *V. uliginosum*. These

results suggest that small patches of *M. albus* in boreal forest sites do not have large consequences for the pollination and reproduction of these subsistence plant species.

However, many of the *M. albus* patches that occur in Alaska are of sizes much larger than the ones we used in our experiment. Of the approximately 2000 *M. albus* records in the Alaska statewide invasive plants database that contain stem count data, 60% were patches of the same size or smaller than the patches we added (< 150 stems; AKEPIC 2015). The other 40% of the records documented larger patches. As a result, the findings from Chapter 2 should not be interpreted as indicating that no management actions should be taken. *M. albus* can produce over 350,000 seeds per plant and spread rapidly (Royer and Dickinson 1999; Conn et al. 2008). Small patches of *M. albus* can quickly become large patches, and we do not know how these larger patch sizes can affect native boreal plant pollination.

Furthermore, several lines of evidence suggest that, even at small patch sizes, *M. albus* acts as a “pollinator magnet” (cf. Lavery 1992) redistributing pollinators in the boreal forest. First, we saw a tendency for sites with *M. albus* added to have greater abundances of pollinators compared to control sites (Chapter 2). Second, we saw increased pollination rates in *R. groenlandicum* flowers 1 - 5 m from the invasive plant patch and decreased pollination at greater distances (8 - 40 m) relative to control sites (Chapter 3). With limited pollinator pools in boreal forest (Kevan et al. 1993) and the ability of pollinators to fly substantial distances to obtain floral resources (e.g., > 300 m for *Bombus* spp.; Osborne et al. 1999; Beekman and Ratnieks 2000; Gathmann and Tschardt 2002; Knight et al. 2005), native plants at greater distances than we measured could be receiving less attention from pollinators when *M. albus* was present and we did not detect it. We found that *M. albus* does alter pollination and reproduction of native plants, though none of the impacts we found were very large. However, the changes in pollinator behavior may be producing unmeasured and unanticipated effects. In terms of invasive

plant management in Alaska, an early-detection and rapid-response approach to small *M. albus* infestations near valued subsistence plant habitat is appropriate.

Linkage B- Citizen science contribution to ecological understanding and management

The Melibee Project citizen science program also increased our understanding of ecological processes within the study system. First, they provided a high quality, independent source of data to validate models of plant reproductive phenology that were derived from herbarium specimens (Chapter 4). Second, the raw data collected through the citizen science program have already informed invasive plant management decisions in several participating communities.

In our model validation effort, the citizen science data provided a means to investigate the strengths and weaknesses of the herbarium dataset. We found that our models were valid for providing an understanding of the relative shifts in phenology of *M. albus*, *V. uliginosum*, and *V. vitis-idaea*, but needed further calibration to provide accurate predictions for specific dates and locations. Using the herbarium-based phenology models, we will predict which parts of Alaska have the greatest overlap in flowering and potential for interaction. Participation in the data collection that will lead to these risk models has proved to be a powerful tool to encourage strategic thinking about invasive plant management, particularly in communities where the harvest of berries for subsistence is highly valued. In the words of one of our citizen science volunteers, Jessica Phillips, Vice President of the Aniak Traditional Council, “The Melibee Project helped me build a strong voice about invasive plants for my council members, for our culture, and way of life in rural Alaska.”

The phenology data gathered by volunteers has already been directly used in the communities where it was collected. In the village of Shageluk, a teacher who had attended one of the 3-day training workshops identified the only known *M. albus* plant in the village. She and

her students collected phenology data on the plant, then pulled the plant before it began producing seeds (J. Hamilton, pers. comm.). In another monitoring site in Seward, the volunteer worked for a local land management non-profit. She used the data she had collected on *M. albus* phenology to plan the timing of local control efforts and a community weed pull event (J. Kain, pers. comm.). While scouting for focal species to monitor in Goodnews Bay, a volunteer noticed an unusual plant and documented the first non-native plant record for her village in the statewide invasive plants database (A. Julius, pers. comm.). These examples suggest the data and the act of collecting data shed new insight on local ecosystems, and in each case, the new ecological knowledge led directly to stewardship and management actions (Fig. 7.1). These applications of the Melibee Project data support the notion that citizen science can help tighten the feedback loops between stakeholders and management actions (an important feature of adaptive co-management in a resilient social-ecological system; Berkes 2002; Tidball and Krasny 2012).

Linkage C- Citizen science and human outcomes

In the literature synthesis in chapter 6, I show how citizen science could improve human capital, social capital, and sense of place, attributes that contribute to the resilience of social-ecological systems (Fig. 7.1C). In addition to this theoretical approach, I gathered some preliminary data to evaluate the impact of the Melibee Project citizen science program on these “human outcomes” in my study system (Appendix A). I used a retrospective pre- and post-survey to document changes in participant knowledge and behaviors that corresponded with each of the human outcomes listed in figure 7.1. The program participants reported increases in their knowledge of relevant science topics such as invasive plant ecology, climate change, and phenology, as well as better understanding of scientific practices like collaboration with other scientists, making observations, and recording data. Comparing their behaviors before they participated in the Melibee Project and after they participated in the program, the volunteers also

reported a significant increase in the frequency in which they took direct action on invasive plants in their community (stewardship actions), engaged in activities that increased their skills or knowledge of invasive plants or other environmental topics (human capital activities), and engaged in social interactions or networks on invasive plants or other environmental topics (social capital activities). Most prominently, the participants reported the largest change in the frequency of their “sense of place” activities, or activities that demonstrated curiosity and awareness about invasive plants and phenology in their daily surroundings. These data set the stage for more rigorous empirical study of the impact citizen science can have on resilience and adaptive capacity. In the meantime, they suggest that citizen science programs can play an important role in engaging the public in invasive plant management.

Linkage D- Impact of metacognitive learning strategies on human capital

Both the empirical study in chapter 5 and literature syntheses in chapter 6 examined the effect that metacognitive learning interventions can have on human capital. The literature review suggested that metacognitive approaches to learning could improve the sorts of thinking skills necessary for problem solving in times of change. However, in my experiment with the Metacognitive Learning Cycle intervention in 7th grade biology classroom, students who received the intervention were no better at applying resilience thinking skills (cf. Box 5.1) to invasive plant problem-solving scenarios than students who did not receive the intervention. These results suggests that in the effort to sustain ecosystem services in the face of non-native plants, rigorous research is required to examine the effectiveness of the strategies we use to teach about them. With the accelerating rate of non-native invasions in the state, Alaska cannot afford to invest time in education strategies that do not effectively give people the knowledge and skills to deal with the issue.

Further directions

Within each chapter, I identified directions for further research on the ecology or education topic presented. The integrated social-ecological systems research framework also offers a way to assess further research needs in the overarching study system (Collins et al. 2011). Each arrow in the model can help identify to important research questions to address. First, it is still unclear if *M. albus* can impact berry harvests. Experiments with larger *M. albus* patch sizes and larger scale assessment of changes in pollinator activity could help provide a better understanding. Within the socio-cultural template of the model, the link between the human outcomes and human behavior is also quite optimistic. Further critical examination of the types of education strategies that consistently lead to effective environmental stewardship actions is clearly necessary. Finally, the linkage between stewardship actions and ecosystem functioning provokes many interesting questions. Are the stewardship actions effective? How do pollinator services to native berry plants change when *M. albus* is removed? Does the effect of the removal vary with the time since introduction, patch size, or level of integration in the plant-pollinator network? The fields of ecology and education have much to offer to help address these sorts of questions. I hope my dissertation will serve as a launching point for the further integration of these research disciplines to help increase our capacity to respond to non-native plant invasions and sustain Alaska's natural resources.

Literature cited

- Beekman M, Ratnieks FLW (2000) Long-range foraging by the honey-bee, *Apis mellifera* L. Functional Ecology 14: 490–496
- Berkes F (2002) Cross-scale institutional linkages: perspectives from the bottom up. Pages 293–321 in Ostrom E, Diez T, Dolsak N, Stern PC, Stovich S, et al. (eds) The Drama of the Commons. National Academy Press, Washington D.C.
- Brown BJ, Mitchell RJ, Graham SA (2002) Competition for pollination between an invasive species (purple loosestrife) and a native congener. Ecology 83:2328–2336
- Burggren WW (2009) Implementation of the National Science Foundation’s “Broader Impacts”: efficiency considerations and alternative approaches. Social Epistemology 23:221–237
- Chittka L, Schürkens S (2001) Successful invasion of a floral market. Nature 411:653
- Collins SL, Carpenter SR, Swinton SM, Orenstein DE, et al. (2011) An integrated conceptual framework for long-term social–ecological research. Frontiers in Ecology and the Environment 9:351–357.
- Conn JS, Beattie KL, Shephard ML, Carlson ML, Lapina I, Hebert M, Gronquist R, Densmore R, Rasy M (2008) Alaska *Melilotus* invasions: distribution, origin, and susceptibility of plant communities. Arctic, Alpine, and Antarctic Research 40:298–308
- Gathmann A, Tschardt T (2002) Foraging ranges of solitary bees. Journal of Animal Ecology 71: 757–764
- Grabas GP, Lavery TM (1999) The effect of purple loosestrife (*Lythrum salicaria* L.; Lythraceae) on the pollination and reproductive success of sympatric co-flowering wetland plants. Ecoscience 6: 230–242

- Graziano G (2011) Strategic plan for invasive weed & agricultural pest management and prevention in Alaska. Alaska Plant Materials Center, Division of Agriculture, Department of Natural Resources, Palmer, AK. 36 pp.
- Kevan PG, Tikhmenev EA, Usui M (1993) Insects and plants in the pollination ecology of the boreal zone. *Ecological Restoration* 8:247–267
- Knight ME, Martin AP, Bishop S, Osborne JL, Hale RJ, Sanderson A et al. (2005) An interspecific comparison of foraging range and nest density of four bumblebee (*Bombus*) species. *Molecular Ecology* 14:1811–1820
- Laverty TM (1992) Plant interactions for pollinator visits: a test of the magnet species effect. *Oecologia* 89: 502-508
- Moragues E, Traveset A (2005) Effect of *Carpobrotus* spp. on the pollination success of native plant species of the Balearic Islands. *Biological Conservation* 122: 611–619
- Osborne JL, Clark SJ, Morris RJ, Williams IH, Riley JR, Smith AD et al. (1999) A landscape-scale study of bumble bee foraging range and constancy, using harmonic radar. *Journal of Applied Ecology* 36: 519–533
- Pace ML, Hampton SE, Limburg KE, et al. (2010) Communicating with the public: opportunities and rewards for individual ecologists. *Frontiers in Ecology and the Environment* 8: 292–298
- Roberts MR (2009) Realizing societal benefit from academic research: analysis of the National Science Foundation’s Broader Impacts Criterion. *Social Epistemology* 23: 199–219
- Royer F, Dickinson R (1999) Weeds of the Northern U.S. and Canada. The University of Alberta Press, Edmonton, Alberta

- Tidball KG, Krasny ME (2012) A role for citizen science in disaster and conflict recovery and resilience. Pg. 226-234 in J .L. Dickinson and R. Bonney. Citizen science: public participation in environmental research. Cornell University Press, Ithaca, NY
- Totland Ø, Nielsen A, Bjerknes AL, Ohlson M (2006) Effects of an exotic plant and habitat disturbance on pollinator visitation and reproduction in a boreal forest herb. *American Journal of Botany* 93:868–873
- Traveset A, Richardson DM (2006) Biological invasions as disruptors of plant reproductive mutualisms. *Trends in Ecology and Evolution* 21:208-216

APPENDIX A:

Report on learning by participants in the Melibee Project citizen science program

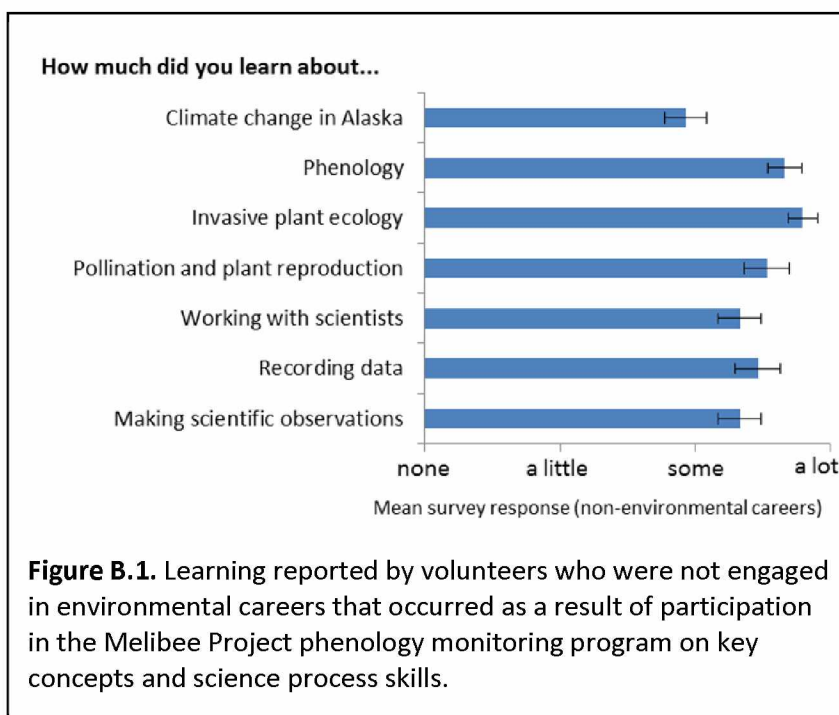


From scientific research to public participation and outreach, the Melibee Project provided rich opportunities for learning. The research team learned from their experiments and observations about the relationships between invasive sweetclover (*Melilotus albus*), pollinators, and native blueberry (*Vaccinium uliginosum*) and cranberry (*Vaccinium vitis-idaea*). Alongside over 240 volunteers, they also learned that the extent of flowering

overlap between the invasive plant and the berries varies across the state. The learning that occurred, however, was not just driven by the sorts of research questions that the Melibee Project asked.

Volunteers who monitored phenology in the Melibee Project Citizen Science Program learned about key ecological concepts and science process skills and changed their behaviors as a result of their learning. Here we present some of the learning outcomes that we documented through internal program evaluations.

Using Likert-scale paper and web-based surveys, we asked participants to gauge how much they learned about the key **ecological concepts** in the Melibee Project, which included climate change in Alaska, phenology, invasive plant ecology, pollination and plant reproduction (0= none, 3=a lot). Survey respondents also identified how much they learned about key **science process skills**, including working with scientists, recording data, and making scientific observations. We also asked program participants to identify the **frequency with which they engaged in ecological learning and stewardship activities** before they participated in the Melibee Project and after they participated in the program (Box 1). The activities on the survey



Box 1

Activities corresponding to different categories of learning outcomes in the Melibee Project volunteer survey. A Likert-scale was used for ranking activity frequency before and after participation in the Melibee Project (6 points: “never,” “once a year,” “a few times per year,” “monthly,” “weekly,” “daily”).

Direct Ecosystem Stewardship

- Pulled invasive plants in your yard or neighborhood
- Attended community weed pull events
- Decided not to plant or buy something because you thought it might be invasive
- Reported invasive plant sightings to land managers or extension agents
- Asked an expert about an unfamiliar plant

Social Capital

- Talked about invasive plants to friends, relatives or acquaintances
- Taught adults or children about invasive plants
- Posted pictures or wrote about invasive plants on social media
- Wrote articles, letters to the editor, listserv emails or creative writing pieces about the issue of invasive plants
- Joined or “liked” environmental or sustainability social media networks

Human Capital

- Attended public lectures on environmental or ecological topics
- Attended courses or workshops on environmental topics
- Participated in other projects where volunteers collect scientific data
- Read magazines, newsletters or online services on environmental issues or ecology
- Volunteered time for an environmental organization or environmental cause

Sense of Place

- Noticed invasive plants around your town
- Noticed invasive plants while travelling away from home
- Paid attention to the changes in plants through the summer
- Paid attention to the changes in animals or fungi through the summer
- Looked up unknown plants in identification books

corresponded with actions that demonstrated changes in ecosystem stewardship (activities that directly benefit the ecosystem), human capital (activities that improve skills and abilities of an individual), social capital (activities that enhance relationships between people that facilitate environmental behavior), and sense of place (activities that demonstrate enhanced wonder and connection to their environment). These four categories of learning outcomes have been shown to **enhance the capacity of a community to respond to environmental changes** such as biological invasions (Tidball and Krasny 2010, Collins et al. 2011).

Twenty-five volunteers responded to our survey (18 female and 7 male; 8 youth age 12-18 and 17 adult; 11 in environmental careers and 14 in non-environmental careers, including students). Of the participants who were students or in non-environmental careers, the greatest learning occurred on the topics of invasive plant ecology and phenology (Fig. B.1). The average of responses from this group indicated that Melibee Project facilitated learning in in all of the key concept and skill areas (fig B.1). Across all respondents, youth

reported learning more about science process skills than adults (average score across science process skills: youth = 2.4, adult = 1.9). Youth and adults both reported similar levels of learning on the key ecological concepts (average score across ecology content areas: youth = 2.4, adult = 2.3).

Compared to before participation in the Melibee Project citizen science program, volunteers reported a significant increase in the frequency they engaged in activities in all four learning outcome

categories (Fig. B.2). The greatest increase occurred in activities associated with “sense of place” (Fig. B.2). Participation in the monitoring project stimulated curiosity and awareness about invasive plants and phenology in people’s daily lives. For example, 48% of respondents reported increasing the frequency that they paid attention to changes in plants in throughout the summer. The second largest increase in activity frequency occurred in the “direct ecosystem stewardship” category. Among these activities, nearly half of the respondents increased their frequency of deciding not to plant or buy something because they thought might be invasive, and 44% increased the frequency with which they pulled invasive plants in their yard or neighborhood. These survey data demonstrate the learning that occurred beyond the Melibee Project research questions to influence the citizen science volunteers’ skills, knowledge, awareness, and behaviors.

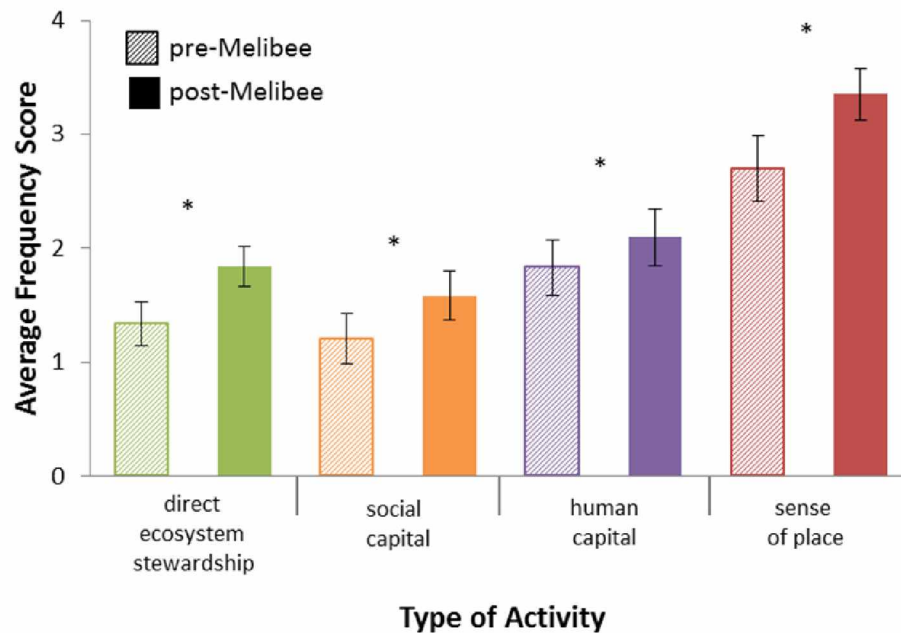


Figure B.2. Average self-reported activity frequency scores in different outcome categories for volunteers before (pre-) and after (post-) their participation in the Melibee Project Citizen Science Program. Statistical differences between pre- and post- Melibee activity frequency (tested using two-tailed t-tests) is indicated by *.

APPENDIX B:

Protocol for the Melibee Project Citizen Science Program

Melibee Project Citizen Science Monitoring Project Monitoring Protocol



Goal: Repeat observations of the same individual plants over a summer, and document the reproductive phenology (timing of flowering and fruiting). University of Alaska Fairbanks ecologists, Dr. Christa Mulder and Katie Spellman, want to see if invasive plants such as white sweetclover (*Melilotus albus*, synonyms: *Melilotus officinalis*, *Melilotus alba*) overlap in flowering time with native blueberry and cranberry plants (*Vaccinium uliginosum* and *Vaccinium vitis-idaea*) in different parts of Alaska. With this phenological data we can create models to help us predict which area might be most vulnerable to changes in pollination of native berry plants. These species are also tracked by the USA National Phenology Network (USA-NPN), and we aligned our protocol to match the requirements of their protocols. Our project will contribute to the National Phenology Network data, which supports larger scale phenology studies throughout the United States.

Project Website: <https://sites.google.com/a/alaska.edu/melibee-project/citizen-science>

Project Contact: Katie Villano Spellman, katie.spellman@alaska.edu

Overview of citizen monitoring steps:

1. Select a site
2. Select plant species to investigate
3. Select individual focal plants
4. Mark your site and plants
5. Record your observations of plants
6. Report your data

1. Select a site

A **site** is the area which encompasses any plants you plan to observe.

Select sites that are

- convenient for you to get to
- relatively uniform habitat
- at least 4 m² in area, but not larger than 100m².

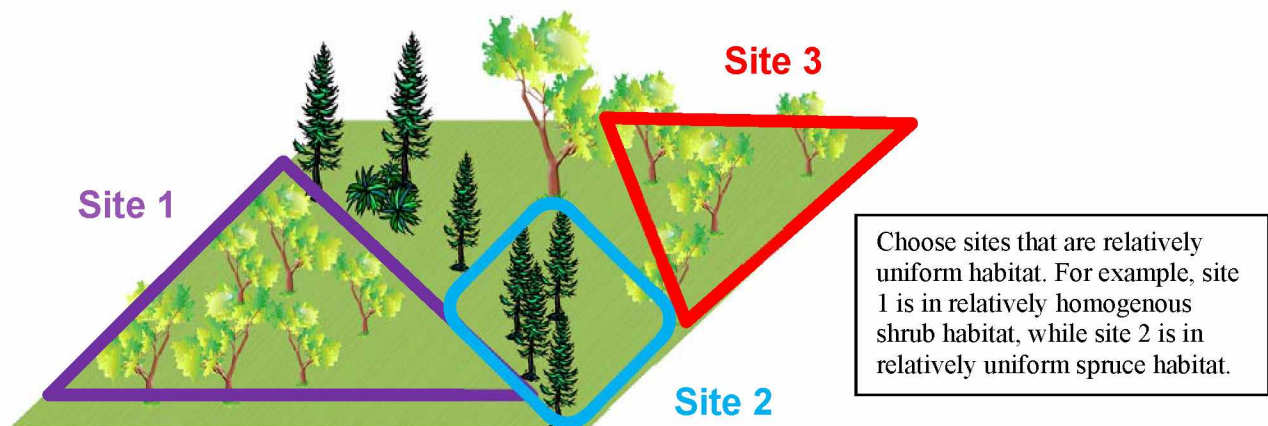


Figure from USA-NPN

Remember, if the land is not publicly owned, be sure to secure permission from the landowner to observe plants on the property.

Try to avoid:

- Steep slopes
- Very windy sites
- Areas prone to snow drifts (this will be hard to avoid for sweetclover sites on the sides of roads where snow plowing has occurred, and it is okay to set up a site there!)
- Watered or fertilized sites

The size of your site will depend on how sparse the species you are observing are on the landscape. If the plants are dense, a small site will work, if the plants are sparse, a larger site will be necessary.

When you've selected your site, fill out the site description form so we can have the relevant data about your site. You can fill out the form on our website or scan and return this form immediately to Katie via email or snail mail it to the address in step 6. You'll need to record the latitude, longitude, and elevation of your site. You can do this with a GPS unit, if you have access to one, or you can use Google Earth to locate the exact location of your site find these numbers.

2. Select plant species to investigate

The focal species we are investigating are *Melilotus albus* (sweetclover), *Vaccinium vitis-idaea* (lowbush cranberry or lingonberry), and *Vaccinium uliginosum* (lowbush blueberry or bog blueberry). Locate one or more of these species in a convenient location for you to monitor on at least a weekly basis. An identification guide is provided for you for our three focal species at our project website <https://sites.google.com/a/alaska.edu/melibee-project/citizen-science/citizen-science-monitoring-instructions>. If you are still unsure if you have the correct species, email us photos and we can make sure you have correctly identified your plants. Do this early on so you don't collect data on the wrong species!

If you do not have *Vaccinium uliginosum*, *V. vitis-idaea* or *M. albus* in your local area, you may choose another native or non-native species tracked by the USA-NPN that occurs in Alaska, or another species of interest. Tracked species include the non-native plants white clover (*Trifolium repens*), or dandelion (*Taraxacum officinale*). You may also choose to observe an invasive plant of interest in your area. We are interested in the phenology of bird vetch (*Vicia cracca*) which is abundant in areas surrounding Fairbanks and Anchorage. Please let us know if you'd like to observe bird vetch.

3. Select individual focal plants

Observing multiple individuals helps to give scientists an idea of the variation in phenology among individuals at your site. You will select and monitor FIVE individuals of the same species at your site. Do not select direct neighbors.

Choose 5 plants that are:

- healthy and REPRODUCTIVE
- relatively undamaged
- At least 20 cm away from other plants you are observing if you are monitoring berries. At least 1 meter away from other plants you are observing if you are monitoring sweetclover.
- For clonal plants, try to choose individual stems from different clumps

Try to avoid:

- plants that are close to buildings

What if the plant I am observing dies?

- Select a new individual to monitor
- Note the death in the comments section of the datasheet
- Give the replacement plant a new, unique label (for example, plant #6)

4. Marking sites and focal plants

You will make your observations repeatedly at the same site or sites over time. You will want to somehow mark your site so that you can find it again in the future. For most sites, it is probably easiest to mark an easy entry point or nearby tree or shrub with colorful flagging, which is a colored non-adhesive tape often made of PVC or vinyl, scrap cloth, or something similar. You can also use natural or human-made landmarks, like the edge of a yard, large rocks, a bend in a trail, a road, or something similar to remember your site location.

Because plant monitoring requires that you observe *the same individual plants* repeatedly, you will also need to mark each plant so that you can find it on each visit. Mark each individual plant with a unique label. For example, you could mark pieces of flagging tape or metal plant tags with “Melilotus-1”, “Melilotus-2”, etc. and then tie them to each of the white sweetclover you are observing. Or, you could label brightly painted popsicle sticks or chopsticks and place them in the ground next to the plant so you can find them as the vegetation grows. Be sure to replace the labels if they get damaged by the weather or animals, so you can be sure to continue marking the correct data for the correct plant.

5. Recording Observations

At least once a week, you will record the phenophase of each focal plant by counting the number of buds, flowers and fruits. You will record these observations on a datasheet. You will record the data for each plant in the column on the data sheet with the same number or label as on the plant. There are different datasheets for sweetclover (*Melilotus albus*) and for the berries (*Vaccinium uliginosum* and *V. vitis-idaea*). Be sure you are using the correct data sheet.

Phenophases:

A picture guide to the phenophases of our three focal species can be downloaded from our project website at <https://sites.google.com/a/alaska.edu/melibee-project/citizen-science/citizen-science-monitoring-instructions>. If you are not sure of a phenophase that you are observing, take a picture and email it to us, and we can help clarify.

Leaf Unfurling/ Emergence

New growth of the plant is visible, either from above-ground buds with green tips, or new green or white shoots breaking through the soil surface. Growth is considered "initial" on each bud or shoot until the first leaf has fully unfolded. Record “yes” or “no” if the plant has begun to unfurl leaves (*Vaccinium* spp.), or has begun to break through the soil surface (*Melilotus albus*). This phase will only need to be recorded in May or early June. You do not need to keep recording this phenophase when the leaves have fully emerged.

Flower Buds

Count the number of flower buds that have not yet opened on the plant. For *Vaccinium uliginosum* (blueberry) the flower buds droop like tiny pink earrings. For *Vaccinium vitis-idaea* (lowbush cranberry), the flower buds look a bit similar to leaf buds at first, as they are both pink in appearance and come straight from the end of the stem. Look for the pinker buds with hardly any green on them. For *Melilotus* sp. (sweetclover), rather than counting every tiny flower, count the

number of inflorescences (flower spikes composed of many small individual flowers) that have unopened buds. There is a special box on the data sheet for sweetclover for inflorescences that are half buds and half flowers, or half flowers and half unripe fruits. Record these numbers separately.

Flowers

Count the number of open, fresh flowers or flower spikes (inflorescences) that are visible on the plant. Flower spikes include many small flowers that usually do not open all at once. There is a special box on the data sheet for sweetclover for inflorescences that are half buds and half flowers, or half flowers and half unripe fruits. Record these numbers separately.

Do not include wilted or dried flowers that remain on the plant, or heads whose flowers have all wilted or dried.

Petal Drop

Count the number of flowers that have dropped their petals, but have not yet started to have their ovaries swell. In all three species, the little green ovaries will not yet look like they are starting to get spherical, and there will be a pointy stigma protruding quite visibly now that the petals are gone.

Unripe Fruits

Count the number of unripe fruits on the plant. For an unripe fruit, the ovary is swollen and obviously has been fertilized. Count all the fruits that are green or beginning to color. For *Melilotus*, count the number of inflorescences that are unripe fruit. Again, record the number of flower spikes with half unripe fruit and half flower or ripe fruit separately.

Ripe fruits

Count the number of ripe fruits that are visible on the plant. In the case of sweetclover, count the number of inflorescences with mature fruits.

Frequency of observations:

- As often as possible, especially during the spring
- At least once a week
- All observations are valuable!

Photographic data:

You can take photos of your plants to help you remember the phenology and identity of the plants. There is a space on the datasheet to record the photo number from your digital camera. Make sure your plant labels are visible in the photo. You can put the site name, plant number, and date on a slip of paper or whiteboard and put this in the photo so you can better keep track of your photos. An example is pictured to the right.



Monitoring sites in areas that you won't be able to revisit:

While monitoring the same plants at the same site throughout the summer is our ideal data, we are also very interested in phenological observations of plants in more remote places that you may only visit once during a summer, like on a backpacking, float trip or remote invasive plants survey. To collect this sort of data follow the above instructions, without marking a site or plants. To select the 5 plants to count the buds/flowers/petal drops/unripe and ripe fruits on, simply toss a pencil over your shoulder and find the nearest plant with flowers or fruits on it to count. Be sure to fill out both a site

description form and an observation datasheet. We would also love to have a photo of the site or a photo of the plants if you are able to provide one.

6. Reporting your data.

Please submit your weekly datasheets once a month to Katie Spellman. You may submit the data in any of the following ways:

- 1) Online at <https://sites.google.com/a/alaska.edu/melibee-project/citizen-science/submit-data>
- 2) Email scanned data sheets to katie.spellman@alaska.edu
- 3) Mail paper data sheets to
Katie Spellman
Biology & Wildlife Department
University of Alaska Fairbanks
PO Box 756100
211 Irving 1
Fairbanks, Alaska 99775

Monitoring kits are available for citizen scientists and monitoring groups participating in our project. Please contact Katie if you are interested in receiving a monitoring kit. The kit includes:

- 5 metal plant tags
- fluorescent flagging tape for marking your site
- “Research Area” laminated sign to mark your site
and prevent tampering
- Focal Plant Identification Guide
- Phenophase Photo Guide for your species
- Monitoring Protocol
- Site Description Form
- Data sheets

Pollinator Attraction Citizen Science Project

Site Description Form



Please fill one out for each site you are making observations in.

Name of Observer(s) _____

Site Location:

Town (or nearest town) _____

Site name (give the site a unique descriptive name) _____

Site location description (describe where your site is located using landmarks)

Site GPS coordinates (in NAD84, decimal degrees)

Latitude _____ °N Longitude _____ °W

GPS precision _____ m Site Elevation _____ m

Site descriptive variables:

Dominant vegetation cover (circle one):

moss/lichen herbaceous shrub tundra tall shrub
deciduous trees coniferous trees

Slope (circle one): flat 0-5% grade 6-10% grade

Aspect (What direction does the site slant toward? Circle one) N NE E SE S SW W NW flat

Focal species for data collection at this site (circle all that apply):

Native plants: Lowbush cranberry (*Vaccinium vitis-idaea*)
 Bog blueberry (*Vaccinium uliginosum*)
 Other native plant of interest _____

Non-Native plants: White Sweetclover (*Melilotus albus*)
 Bird Vetch (*Vicia cracca*)
 Other non-native plant of interest _____

Additional notes or comments about the site:

Pollinator Attraction Citizen Science Project Observation Datasheet

for Bog Blueberry (*Vaccinium uliginosum*) or
Lowbush Cranberry (*Vaccinium vitis-idaea*) or
other species



Please fill out the following datasheet once a week for each site. A different sheet must be used for each site. If you are monitoring more than one species at your site, use a new sheet for each species.

Observer name _____ Site Name _____

Date _____ Time of observation _____

Temperature _____ Weather (circle one) sunny partly cloudy cloudy rain

Plant phenology data: Species _____

		Focal plant 1	Focal plant 2	Focal plant 3	Focal plant 4	Focal plant 5
Plant label						
Photo number (optional)						
Phenophase	Leaf unfurling / Emergence	Y N	Y N	Y N	Y N	Y N
	Flower buds					
	Open flowers					
	Petal Drop					
	Unripe fruit					
	Ripe fruit					
Additional notes about the plant						

General notes:

Pollinator Attraction Citizen Science Project **Observation Datasheet** for Sweetclover (*Melilotus albus*)



Please fill out the following datasheet once a week for each site. A different sheet must be used for each site.

Observer name _____ Site Name _____

Date _____ Time of observation _____

Temperature _____ Weather (circle one) sunny partly cloudy cloudy rain

Plant phenology data:

		Focal plant 1	Focal plant 2	Focal plant 3	Focal plant 4	Focal plant 5
Plant label						
Photo number (optional)						
Phenophase	Leaf unfurling / Emergence	Y N	Y N	Y N	Y N	Y N
	Flower buds					
	½ bud, ½ flower					
	Open flowers					
	½ flower, ½ petal drop					
	Petal Drop					
	½ petal drop, ½ unripe fruit					
	Unripe fruit					
Ripe fruit						
Additional notes about the plant						

General notes: